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**What's the Damage?
Environmental Regulation
with Policy-Motivated
Bureaucrats**

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Summary

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JEL Classification: D73, D82, C61, Q52, Q58

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January 31, 2014

Abstract

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1 Introduction

Environmental regulation – that is, internalization of environmental externalities – is an important and widely accepted policy goal. However, many real-world environmental-policy issues are characterized by a high degree of complexity. It is necessary to understand the natural processes, to estimate damage and abatement costs, and to choose and implement the right policy instruments.

For these reasons, policy makers usually are not capable to implement these policies on their own, but depend on expert knowledge, which is held by an administrative bureaucracy (see Drazen, 2000, p. 686–689), the *environmental agency*. Due to its expertise, such an agency has a large leeway in shaping policy. For example, its officers can be expected to be in a better position to judge the potential environmental impact of carbon dioxide emissions, exhaust gases, oil spills, or fracking. This information is then often basis for policy decisions.

This expert knowledge would be of little interest if either voters (or elected politicians) could select the environmental agency staff to ensure that they have the same preferences as the public, or agency staff were just neutral analysts. However, the bureaus are usually located in a permanent administrative apparatus, so it is unlikely that experts could be replaced at will.

Moreover, environmental regulation agency staff often have a personal interest in matters concerning the environment, and a strong own position about questions of environmental policy. When analyzing the effects of delegation to environmental agencies, this policy motivation is an important feature.

Young eco-activists, for example, may choose fields of study that, intentionally or as a side effect, qualify for governmental services in this field. Then again, some may suspect environmental regulators of being biased towards the industry,¹ possibly being too familiar with those they should regulate (cf. Muehlen-

¹For example, in responding to an internal-evaluation survey, 29% of BOEMRE (the former U.S. Bureau of Ocean Energy Management, Regulation and Enforcement) staff responsible for environmental and cultural resource protection either disagreed or were neutral about the statement “Overall, BOEMRE ensures that drilling and production activities protect the environment and cultural resources” and the report states that “respondents repeated the concern throughout the survey that FO [division, which deals directly with operators] was too pro-industry” (Kendall,

bachs et al., 2013) or showing preemptive obedience to raise the chance of later employment opportunities.

Thus, while optimal policy would obviously be based on the true environmental impact of an economic activity, the regulation staff might have an incentive to misrepresent the truth to get closer to their own preferred policy. The combination of bias and asymmetric information leads to an agency problem in which the regulator is the informed agent, and the government is the uninformed principal.

In this paper, we discuss how a benevolent government designs an incentive-compatible tax and reward schedule – a contract – for a regulatory expert who has an exogenously given environmental-policy bias.² The government is uncertain about the environmental impact of some externality. The impact is revealed to the agent, and an environmental policy is chosen based on the agent's statement. For concreteness, the asymmetric information is about the marginal environmental damage of energy usage, in short referred to as *impact*, and the policy is an energy tax.

Thus, in the usual wording of principal-agent models, the true impact is the agent's *type*. The rewards are modeled as a monetary payment to the agent. However, they should be understood broadly: Budgets, office endowments, or promotions might be more common than plain payments, and have similar features as our model's rewards, as long as the principal would not like to give them away for free. In equilibrium, rewards and the tax depend on the agent's statement about environmental impacts in a way that makes truth-telling optimal. For some realizations of the environmental impact, the agent will receive an *information rent* to disincentivize under- or overstating. This rent is a combination of, firstly, the reward, and, secondly, the tax level being a compromise between the principal's and the agent's preferred policy.

In our setting, we find that the agent, independently of how much he dislikes environmental damage, has, on the one hand, an incentive to overstate the im-

2010), which suggests that either BOEMRE in total or these 29% may be biased.

²Throughout the paper, we do not explicitly model a government or elections. Instead, we assume that the government acts as a principal representing the citizens' interest.

pact. The reason is that a higher environmental impact would, *ceteris paribus*, lead to higher environmental damage or less production. This implies less utility for the agent, due to his political preferences, and thus worsens his situation *within* the contract. To accept the contract nonetheless, he would get a higher compensation. Because a high compensation is attractive for all types, there is an incentive to claim high impact even though it is in fact low. The impact being the agent's type, "low types" should receive an information rent to disincentivize overstating.

On the other hand, the shape of optimal contracts also depends on how the agent's utility changes with his type if he does not take part in the contract. In most principal-agent models, this *outside utility* is fixed for all types. In our setting of politically-motivated agents, this is not plausible; high environmental damage costs decrease the utility of every inhabitant of the economy. Thus, stating a high impact would also tell the principal that the agent's outside option is low. Technically, the agent's participation constraint decreases with his type.

Additionally, while the agent will clearly not receive a monetary reward if he turns down the proposed contract, we need an assumption how policy is chosen in this case. We assume that he can implement his preferred environmental policy. This represents, though in an admittedly extreme way, a bureaucracy's factual discretion (and it frees us from the need to model an additional stage outside the contract).

Because the agent's utility is lower both within and without the contract if his type is high, we have a situation of *countervailing incentives* as pioneered by the work of Lewis and Sappington (1989). Building on the general solution strategy proposed in Maggi and Rodríguez-Clare (1995) and Jullien (2000), we are able to derive the equilibrium tax and reward schedule. We find that for an agent who is less (more) environmentally concerned than the government, the understating (overstating) incentive dominates in equilibrium.

The resulting equilibrium contract is quite intuitive. Firstly, we find that incentive compatibility requires offering an information rent to an environmental

expert who is less (more) environmentally concerned than the government if he “admits” a high (low) damage realization. Moreover, there is an equivalent to the well-known “no distortion at the top” result: With a less (more) environmentally concerned agent, the asymmetric-information friction vanishes for the tax with the highest (lowest) impact realization (but the agent receives the highest information rent then, which consequently consists of a payment only).

Secondly, the influence of the agent's preferences on the tax is higher if he cares less for monetary rewards. Thirdly, depending on the model parameters, there may be an interval of types for which no information rent is being paid and the participation constraint is binding. To put it another way, if the environmental agency is less (more) environmentalist than the government, then for a range of high (low) realizations of the impact the government will leave the policy choice to the agency, and will thus neither pay rewards nor enforce a more favorable tax.

The equilibrium tax structure reveals that (on an interval where the participation constraint is not binding) an increase in the expected impact will unambiguously increase the tax, irrespective of the agent's preferences concerning the environmental damage. A mean-preserving spread of the damage distribution, however, increases the tax for environmentally concerned agents (and vice versa). A main insight here is to understand different policy reactions to environmental externalities with (ex-ante) different impact distributions, and their interaction with the information asymmetry between the government and environmental agency.

The literature on environmental regulation has extensively analyzed information asymmetries. The informed party in the literature are firms that know their abatement costs, and their counterpart is a neutral welfare-maximizing regulator that designs a contract for the firms (see, e.g., Hoel and Karp, 2002, Kwerel, 1977, Laffont and Tirole, 1993, Lewis, 1996, Spulber, 1988). Also, damage costs may be uncertain, but not due to asymmetric information.

Our contribution adds a new perspective on agency problems in environmen-

tal regulation by analyzing information asymmetries between the government and environmental bureaucrats.³ This information asymmetry could, in principle, concern abatement costs as well. However, the case that is more specifically related to the experts of our model is asymmetric information about environmental impact and damage costs. Thus, the paper analyzes an additional distortion that has to be taken into account when considering environmental regulation.

The paper proceeds as follows. In Section 2, we discuss the literature on political agency and environmental regulation and its relation to this paper. Section 3 lays out the economy that is the microfoundation of our principal's and agent's utility-functions. Section 4 derives a benchmark, namely agency under perfect information. Section 5 develops the asymmetric-information agency model, derives the optimal contract and discusses its comparative statics. Finally, Section 6 summarizes. The derivation of the optimal contract, among other things, is discussed in the appendix.

2 Relation to the Literature

Our model takes place in an adverse-selection environment, in which a decision-relevant variable is private knowledge of the agent. As usual in such models, the principal's optimal contract incentivizes to tell the truth. The agent's bliss point – that is, the value of his choice variable that he would prefer – differs from that of the principal. Note that in standard adverse-selection models (cf. Laffont and Martimort, 2001), the agent's bliss point is a corner solution. Usually, workers want to work as little as possible, customers do not want to pay if they can get their products for free, etc.

In our model, the agent's bliss point is an interior solution because he cares for the effects of policy.⁴ There is an optimal policy for each true state of the

³However, in an empirical study, Muehlenbachs et al. (2013) stress the problem of biased environmental *enforcement* agents.

⁴Some environmental-policy issues in the real world will require corner solutions, which could be regarded as a special case.

world, but the agent's preferences concerning this bliss point differ from those of the government. Both the assumption that policy results enter a utility function and that they do so in a specific way require a motivation. For example, Harrington (1993) assumes that the results of policy enter the agent's (who is in his case a politician) utility functions due to altruism, or because the agent is part of the economy and policy has the same effect on him as on everybody else. Transferring the vocabulary from politician models, the bureaucrat expert in our model could be described as *partisan* or *ideological* or just as *policy-motivated* (cf. Callander, 2008).

From a different perspective, the policy-related utility function of the agent in our model may show that he is "mission-oriented" or intrinsically motivated. Such agents have been characterized by Besley and Ghatak (2005) in the context of public-sector organizations and bureaucracies, and other "mission-oriented" organizations. Murdock (2002) models the relation between a firm and motivated agents in an implicit-contract setting.

Epstein and O'Halloran (1994) also consider the conflict between the government and an agency with differing policy goals. They discuss the optimal amount of discretion. In our paper, there is an endogenously chosen range of realizations of the damage function for which the agency has discretion, but we consider payment schedules, a different policy setting, and focus on information asymmetries. To motivate the agency's preferences, Epstein and O'Halloran argue that they "may be derived from private political values, personal career objectives, or, all else equal, an aversion to effort".

Additionally to political preferences, agents in our model receive monetary transfers to compensate them for deviating from their preferred tax rate. We derive optimal *payment schedules* for the agent. In recent years, a large literature on the effects of paying political agents has developed, with both theoretical and empirical papers. This literature, however, focuses on the effects of the level of payment on political selection, particularly the effects on competition for office (cf. Besley, 2004, Gagliarducci and Nannicini, 2013, Kotakorpi and Poutvaara,

2011, Messner and Polborn, 2004).⁵ By contrast, the agent in our model should be thought of as a regulatory bureaucrat who already is in office. The contract is meant to influence his behavior *after* he has been selected.

In the context of the political-agency literature, the mixed motivation of policy outcomes and payments has been modeled by Breton and Salanie (2003) and Martimort and Semenov (2007a,b, 2008). In these papers, the “payment” component comes from contributions offered by lobby groups in exchange for favorable policy. Their models feature asymmetric information concerning the government’s ideology (instead of asymmetric information about the state of the world as in our model).

The idea that asymmetric information in political agency leads to political agents misrepresenting the truth to get nearer to their own bliss point is analyzed in models of signaling and elections by, for example, Schultz (1995, 2002). In Schultz (2002), the government has private knowledge about its own preferences and the economy and uses policy for signaling, while in Schultz (1995) information transmission takes the form of a cheap-talk game.

In our model, we analyze the effects of different degrees of environmentalism of an agency. However, we do not discuss the situation in which the government endogenously can appoint some agent with specific environmental preferences (typically more environmentally concerned agents) to overcome e.g. time-consistency problems (as Helm et al., 2003, 2004 or Heyes and Kapur, 2010) or bargaining between firms and a regulator (as Amacher and Malik, 1996). Our model, which is set in a different context, further discusses the trade-offs of such delegation with differing preferences.

⁵Other papers in this literature are more specifically concerned about the effects of politicians’ outside options (see Becker et al., 2009).

3 The Model

3.1 The Economy

We focus on a very stylized economy that is inhabited by a continuum of measure 1 of identical consumers with utility given by:

$$u = c - D, \quad (1)$$

where c is consumption, and D is environmental damage. An individual's budget constraint is

$$c = p_L \cdot L + t, \quad (2)$$

where t are lump-sum transfers, L is the consumer's labor time endowment (which he supplies inelastically), and p_L is the wage. Due to the unit size economy, L is average and total endowment, and t are average and total transfers.

Firms competitively produce some consumable output Y using energy E and labor L as inputs:⁶

$$Y = A \cdot L^{1/2} \cdot E^{1/2}, \quad (3)$$

where A denotes technology. Profit is

$$\pi = Y - p_L \cdot L - (p_E + \tau) \cdot E, \quad (4)$$

where p_E is the net energy price and τ an energy tax. With p_E being given by the world market, and L by the economy's endowment, the usual profit-maximization leads to the following equilibrium:

⁶ This explicit functional form enables us to derive closed-form solutions.

$$E = \left(\frac{1}{2} \cdot \frac{A}{p_E + \tau} \right)^2 \cdot L, \quad (5)$$

$$p_L = \left(\frac{1}{2} \cdot A \right)^2 \frac{1}{p_E + \tau}, \quad (6)$$

$$Y = \frac{1}{2} \cdot \frac{A^2}{p_E + \tau} \cdot L. \quad (7)$$

We assume environmental damage to depend linearly on the amount of energy that firms use in production:

$$D = \theta \cdot E, \quad (8)$$

and in equilibrium, this is

$$D = \theta \cdot \left(\frac{1}{2} \cdot \frac{A}{p_E + \tau} \right)^2 \cdot L. \quad (9)$$

Income of the economy is $p_L L$, so both income and environmental damage D depend on the tax. The economy faces a trade-off in setting the tax optimally.

3.2 The Environmental Agency

The only role of the government in our model is to raise a Pigou tax. The tax receipts net of payments r to the regulatory agent are distributed to the population. Therefore, the government's budget equation is

$$\begin{aligned} t &= \tau \cdot E - r \\ &= \tau \cdot \left(\frac{1}{2} \cdot \frac{A}{p_E + \tau} \right)^2 \cdot L - r. \end{aligned} \quad (10)$$

We assume regulatory agents to be separate from the rest of the economy: They do not take part in the labor market, and they have partly policy-related utility functions.⁷

⁷For a similar approach in modeling political agent's preferences, see Acemoglu et al. (2008, 2011).

An agent's utility is

$$w = (1 + \zeta) \cdot r + c - \gamma \cdot D, \quad (11)$$

where c is the economy's average consumption and ζ and γ are preference parameters: ζ reflects how much the agent weights the payments and γ is his weight on environmental damage. Both parameters are positive. In case of γ , this just means that the agent has a disutility from environmental damage. In case of ζ , it means that his weight of r in the utility function larger than 1. This requirement for the implementability of optimal contracts will be discussed later.

3.3 Equilibrium Utility

Equations (1), (2), (6), (9), (10), (11) yield equilibrium utility of the consumer and the regulatory agent as functions of the environmental impact θ , the tax τ , and the payment r :

$$u(\theta, \tau, r) = \left(\frac{1}{2} \cdot A\right)^2 \left[\frac{1}{p_E + \tau} + \frac{\tau - \theta}{(p_E + \tau)^2} \right] \cdot L - r, \quad (12)$$

$$w(\theta, \tau, r) = \left(\frac{1}{2} \cdot A\right)^2 \left[\frac{1}{p_E + \tau} + \frac{\tau - \gamma \cdot \theta}{(p_E + \tau)^2} \right] \cdot L + \zeta \cdot r, \quad (13)$$

We normalize $A = 2$ and define $\chi \equiv 1/\zeta$ (which simplifies the notation in later sections). Thus, we write

$$u(\theta, \tau, r) = \left[\frac{1}{p_E + \tau} + \frac{\tau - \theta}{(p_E + \tau)^2} \right] \cdot L - r, \quad (14)$$

$$w(\theta, \tau, r) = \left[\frac{1}{p_E + \tau} + \frac{\tau - \gamma \cdot \theta}{(p_E + \tau)^2} \right] \cdot L + \frac{r}{\chi}. \quad (15)$$

The *laissez-faire* optimum of the agent (denoted by a subscript *lf*), i.e., a situation where he forgoes his career track but can discretionarily choose the Pigou tax, is

$$\tau_{lf}(\theta) = \gamma \cdot \theta \quad (16)$$

and it would yield a utility level of

$$w(\tau_{lf}(\theta), \theta, r) = \frac{L}{p_E + \gamma \cdot \theta} + \frac{r}{\chi}. \quad (17)$$

In this paper, “laissez-faire” does not refer to the nonexistence of taxes, but to a situation “where the decision-maker is freed from any influence” (Martimort and Semenov, 2008), and thus chooses his bliss-point policy. Also, we define by

$$\omega_{lf}(\theta) \equiv w(\tau_{lf}(\theta), \theta, 0) \quad (18)$$

the utility level that the agent can reach if he gets no payment but implements his laissez-faire policy.

4 Environmental Policy: Symmetric-Information Benchmark

Before turning to our asymmetric-information model, it is helpful to consider a full-information benchmark version first. Thus, both the principal and the agent know θ .

What is the role of the environmental agency in this setting? The first, intuitive answer is that the government needs the agency to set the tax. But then, what happens if the agency refuses to cooperate? If the government could just set its preferred tax without using the agency, there would be no need of the agency in the first place. Thus, as a consistent way of modeling the relation between the government and the agency, we assume that the agency can implement its preferred policy. The government has to offer a compensation to get different policy.⁸ This can be seen as a pure *agency friction* in our model, additional to the *information friction* discussed later.⁹

⁸This may be an extreme assumption about the bureaucracy's power, but not more “ad hoc” than other solutions like, say, a zero-tax fallback option.

⁹This setting is similar to the agency problem in the interest-group common-agency papers in the spirit of Grossman and Helpman (1994). In this literature, lobby groups offer monetary

Thus, the principal's problem is to maximize (14), subject to

$$w(\theta, \tau, r) - \omega_{lf}(\theta) \geq 0. \quad (19)$$

The Lagrangian is

$$\mathcal{L} = u(\theta, \tau, r) + \mu \cdot [w(\theta, \tau, r) - \omega_{lf}(\theta)], \quad (20)$$

with the first-order conditions

$$-\frac{\tau - \theta}{\tau - \gamma\theta} = \mu \quad (21)$$

for the choice of τ , and

$$\chi = \mu \quad (22)$$

for the choice of r , and the Kuhn-Tucker condition

$$\mu \geq 0 \quad w(\theta, \tau, r) - \omega_{lf}(\theta) \geq 0 \quad \mu \cdot [w(\theta, \tau, r) - \omega_{lf}(\theta)] = 0. \quad (23)$$

Thus, μ is the shadow price of relaxing the agent's utility constraint. (21) balances the effect the tax has on the principal's utility with its effect on the agent's. So does (22) for the payment. Together, the equations reflect the fact that any change of the tax that worsen's the agent's situation must be compensated, and from the principal's perspective the price for a change in the tax is $\chi = 1/\zeta$ at the margin. Thus, χ is the principal's utility loss for every unit of additional agent's utility gained by transferring money. Hence, it is the price of "buying" agent's utility.

This now rationalizes the aforementioned restriction $\zeta > 0$. If this was not true, the price for "buying" agent's utility would be negative, dissolving the principal's problem. The reason for this is that part of the agent's utility function contributions to the government in exchange for a deviation from its bliss-point policy.

reflects some benevolence; he cares for the economy's consumption. The monetary transfer to the agent reduces the lump-sum redistribution of tax revenues to consumers. Thus, if the agent would value a consumption unit more if it is consumed by them and not by himself, which would be implied by $\zeta < 0$, he would benefit from a negative transfer.

Because χ is positive, (23) implies that the agent is always kept on his outside-option utility level in the principal's optimum. Put another way, compensating the agent is costly for the principal, so he wants to give as little as possible.

The optimal tax as a function of the environmental impact is:

$$\tau(\theta) = \tau_{fb}(\theta) := \frac{1 + \gamma\chi}{1 + \chi} \cdot \theta. \quad (24)$$

The subscript *fb* is for "first-best" because $\tau_{fb}(\theta)$ is the tax that can be implemented if there is no information asymmetry. (However, note that it is "first-best" subject to the agency constraint.)

If $\gamma = 1$, the agent will always do what the principal likes best, so there is no need for deviations from his preferred tax $\tau = \theta$. For any other $\gamma > 1$, the tax is too high from the principal's point of view, $\tau(\theta) > \theta$, and too low from the agent's, $\tau(\theta) < \gamma\theta$ (and vice versa). The compensation payment is

$$r(\theta) = \left[\frac{\chi\theta(\gamma - 1)}{p_E + \theta + \chi(p_E + \gamma\theta)} \right]^2 \cdot \frac{L}{\chi(p_E + \gamma\theta)}. \quad (25)$$

This payment is non-monotonic, and it has a maximum for

$$\theta = \frac{1 + \chi}{1 + \gamma\chi} \left[1 + \sqrt{1 + 8 \frac{1 + \gamma\chi}{\gamma(1 + \chi)}} \right] p_E. \quad (26)$$

Intuitively, this is so because a change in θ has two countervailing effects on the trade-off faced by the principal in order to motivate the agent to participate in the contract. On the one hand, the agent's laissez-faire utility level is decreasing in θ . Thus, the payment r to induce the agents to participate decreases. On the

other hand, the utility level of participating in the contract decreases. This forces the principal to increase the payment for any given tax rate τ . It turns out that the first (second) effect dominates for large (small) θ , no matter whether γ is smaller or larger than unity.

In the following section, we add asymmetric information. For ease of exposition, we drop the compensation payment and instead focus the discussion on the equilibrium tax and the agent's equilibrium information rent. For the tax, (24) serves as a benchmark.

5 Regulation under Asymmetric Information

5.1 Order of Moves

We assume that, firstly, a bureaucrat in the environmental agency (in the following “the agent”) is appointed to office by the government (in the following “the principal”). The agent's preference parameters γ and χ are revealed when the agent is appointed; they deviate from those of the principal.¹⁰

Secondly, when the agent has been appointed to office, the principal offers a contract to the agent. The contract specifies policy and a payment as a function of θ' , which is the agent's assertion about the environmental-impact parameter θ . Thirdly, nature draws θ from a distribution $F(\theta)$. This distribution is common knowledge.¹¹ θ is then revealed to the agent, who then asserts θ' . Finally, policy and payment are realized as specified in the contract.

As in the symmetric-information benchmark in Section 4, we assume that the principal cannot set policy on his own. Moreover, we assume that any damage is realized after all stages of the game are completed, so that punishment contracts are not implementable.¹²

¹⁰We do not consider the stage of appointment under uncertainty about the agent's preferences because we concentrate on the agency conflict in office.

¹¹Equivalently, we may assume that θ is fixed at a constant value which is unknown ex-ante. $F(\theta)$ then represents common beliefs about how likely different values of θ are.

¹²Alternatively, assume that ex-post liability is not feasible for exogenous reasons, like verifiability problems.

5.2 The Optimization Problem

θ is the agent's private information. In the moment when it is revealed, it becomes, in effect, an unobservable characteristic of the agent. Thus, we have a hidden-characteristics principal-agent setting where θ is the agent's type. The principal offers a contract $(\tau(\theta'), r(\theta'))$, in which he makes the tax and the agent's reward payment functions of his claim θ' . Given such a contract, the utility of the agent net of his outside-option $\omega_{lf}(\theta)$ is:

$$\Delta(\theta, \theta') = v(\theta, \theta') - \omega_{lf}(\theta), \quad (27)$$

where the agent's utility (in the contract) is given by substituting the contract in (15):

$$\begin{aligned} v(\theta, \theta') &= w(\theta, \tau(\theta'), r(\theta')) \\ &:= \left[\frac{1}{p_E + \tau(\theta')} + \frac{\tau(\theta') - \gamma \cdot \theta}{(p_E + \tau(\theta'))^2} \right] \cdot L + \frac{r(\theta')}{\chi}. \end{aligned} \quad (28)$$

The agent will choose θ' to maximize Δ . The first-order condition is:

$$\frac{\partial \Delta(\theta, \theta')}{\partial \theta'} = 0. \quad (29)$$

Note that this implies that the principal offers to let a tax be implemented that is ex-post suboptimal from his point of view. Thus, we assume that the principal is able to commit to such a behavior. This may be more plausible if we assume that the agent directly chooses and implements a tax; however, in the model the choice of θ' is equivalent to that.

Incentive-compatible (or "truthful") contracts, that make $\theta' = \theta$ optimal,¹³

¹³That is, the agent does not lie about θ if the contract is incentive-compatible. The condition in (29) is a local result. To ensure global incentive compatibility it must also be true that the *monotonicity constraint* (Fudenberg and Tirole (1991), Theorem 7.2.) $\tau'(\theta) \geq 0$ holds – see Appendix A.1 for a more detailed discussion of incentive compatibility.

lead to the following indirect net utility function:¹⁴

$$\Delta(\theta, \theta' = \theta) = \Delta(\theta) = v(\theta) - \omega_{lf}(\theta), \quad (30)$$

so that the *incentive-compatibility constraint* of an optimal contract is

$$\Delta'(\theta) = \frac{\partial \Delta(\theta, \theta')}{\partial \theta} = - \underbrace{\frac{\gamma L}{(p_E + \tau(\theta))^2}}_{v'(\theta)} - \omega_{lf}'(\theta). \quad (31)$$

Equation (31) shows how the agent's utility must change with θ to ensure truth-telling, i.e., to disincentivize lying about the environmental impact. The interpretation of this condition is standard (see Maggi and Rodríguez-Clare, 1995). On the one hand, the agent has an incentive to overstate θ because a higher θ would make him worse off within the contract relation, which would lead to higher compensation. This is reflected in the first term on the right-hand side of equation (31). The optimal contract has to take into account that, with only this effect being present, the utility of higher θ -types must decrease in the described way to avoid this overstating of the true impact.¹⁵

On the other hand, however, the agent's outside option also depends on θ . If it is high, the agent's utility outside the contract is low. Thus, the agent may want to understate the environmental impact to let his utility outside of the contract appear better, to receive higher compensation for participating in the contract. This effect calls for an increase in the agent's net-utility in θ .

Taking both effects together, it is unclear whether the net-utility (i.e., the information rent) is increasing or decreasing with the true θ (see Jullien, 2000). In contrast to standard principal-agent problems (i.e., those with a type-independent outside option), it is then unclear which type will earn zero information rents.

Incentive compatibility poses a restriction on the evolution of net-utility, nar-

¹⁴We denote in the following, with a slight abuse of notation, the indirect utility function and the net utility function of the agent by $v(\theta)$ and $\Delta(\theta)$, respectively, given that truth-telling is optimal.

¹⁵See Kaplow (2010) for a nice interpretation.

rowing the space of implementable contracts. However, the principal also has to ensure that the agent will participate in the contract, which requires

$$\Delta(\theta) \geq 0. \quad (32)$$

Solving (28) for the transfer r , assuming truth-telling, and plugging into (14), the principal's utility can be written

$$\begin{aligned} & u(\theta, \tau(\theta), \Delta(\theta)) \\ &= \left[\frac{1 + \chi}{p_E + \tau(\theta)} + \frac{\tau(\theta) - \theta + \chi \cdot (\tau(\theta) - \gamma \cdot \theta)}{(p_E + \tau(\theta))^2} \right] \cdot L - \chi \cdot \omega_{lf}(\theta) - \chi \cdot \Delta(\theta). \end{aligned} \quad (33)$$

With a density $f(\theta)$, expected utility is

$$\begin{aligned} U &= \int_{\underline{\theta}}^{\bar{\theta}} f(\theta) \cdot d\theta \\ &\cdot \left\{ \left[\frac{1 + \chi}{p_E + \tau(\theta)} + \frac{\tau(\theta) - \theta + \chi \cdot (\tau(\theta) - \gamma \cdot \theta)}{(p_E + \tau(\theta))^2} \right] \cdot L - \chi \cdot \omega_{lf}(\theta) \right. \\ &\quad \left. - \chi \cdot \Delta(\theta) \right\}. \end{aligned} \quad (34)$$

The expression in square brackets is the total surplus, net of the outside option of the agent from implementing a Pigou tax. In our benchmark case without information asymmetries but the need to appoint some environmental agent, $\tau(\theta)$ maximizes this expression. Taking the informational friction into account, however, the principal has to leave an additional rent to the agent to ensure truth-telling. This leads to an (additional) inefficiency.

5.3 Equilibrium Taxes under Information Asymmetry

Under the assumption of an ex-ante uniformly distributed environmental impact,¹⁶ solving the optimization problem leads to the following equilibrium tax $\tau^*(\theta)$ structure.

¹⁶This is formalized as Assumption A.1 in Appendix A.2.

Proposition 1 (Equilibrium tax paths).

- For $\gamma < 1$, we have from (A.40):

$$\tau^*(\theta) = \begin{cases} \gamma\theta & \forall \theta \leq \hat{\theta}, \\ \tau_{fb}(\theta) - \frac{1-F(\theta)}{f(\theta)} \frac{\chi\gamma}{1+\chi} = \frac{1+\gamma\cdot\chi}{1+\chi} \cdot \theta - \frac{\gamma\cdot\chi}{1+\chi} \cdot (\bar{\theta} - \theta) & \forall \theta > \hat{\theta}, \end{cases} \quad (35)$$

where $\bar{\theta}$ is the upper bound of the θ distribution, $\hat{\theta} = \frac{\chi}{\chi - \frac{\gamma-1}{\gamma}} \bar{\theta}$, and

$$\Delta^{*'}(\theta) \begin{cases} = 0 & \forall \theta \leq \hat{\theta}, \\ > 0 & \forall \theta > \hat{\theta}. \end{cases} \quad (36)$$

- For $\gamma > 1$ and $\chi - (\gamma - 1)/\gamma > 0$, we have from (A.48):

$$\tau^*(\theta) = \begin{cases} \tau_{fb}(\theta) + \frac{F(\theta)}{f(\theta)} \frac{\chi\gamma}{1+\chi} = \frac{1+\gamma\cdot\chi}{1+\chi} \cdot \theta + \frac{\gamma\cdot\chi}{1+\chi} \cdot (\theta - \underline{\theta}) & \forall \theta < \check{\theta}, \\ \gamma\theta & \forall \theta \geq \check{\theta}, \end{cases} \quad (37)$$

where $\underline{\theta}$ is the lower bound of the θ distribution, $\check{\theta} = \frac{\chi}{\chi - \frac{\gamma-1}{\gamma}} \underline{\theta}$, and

$$\Delta^{*'}(\theta) \begin{cases} < 0 & \forall \theta < \check{\theta}, \\ = 0 & \forall \theta \geq \check{\theta}. \end{cases} \quad (38)$$

- For $\gamma > 1$ and $\chi - (\gamma - 1)/\gamma \leq 0$, we have from (A.48):

$$\tau^*(\theta) = \tau_{fb}(\theta) + \frac{F(\theta)}{f(\theta)} \frac{\chi\gamma}{1+\chi} = \frac{1+\gamma\cdot\chi}{1+\chi} \cdot \theta + \frac{\gamma\cdot\chi}{1+\chi} \cdot (\theta - \underline{\theta}) \quad (39)$$

and

$$\Delta^{*'}(\theta) < 0. \quad (40)$$

Proof. See Appendix A.2. □

Figure 1 and Figure 2 demonstrate the results for $\gamma < 1$ and $\gamma > 1$, respec-

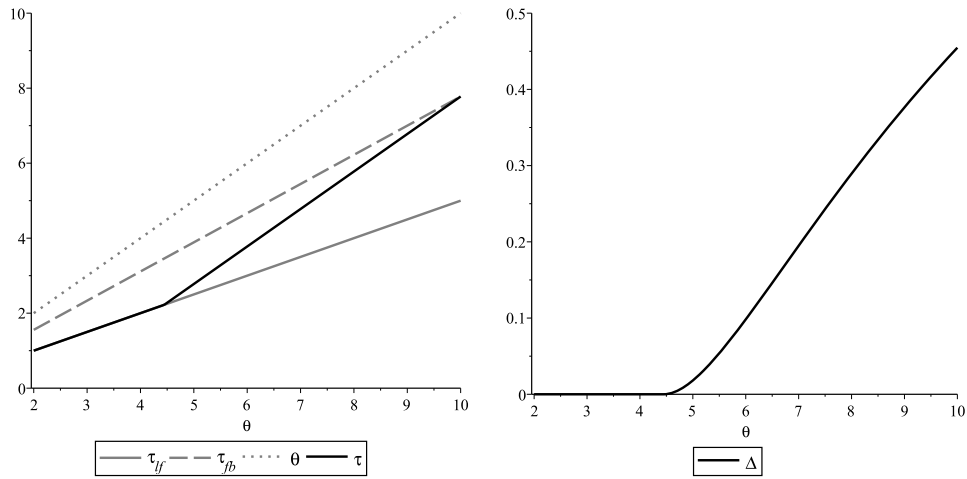


Figure 1: Illustration for $\gamma < 1$. Parameters: $\gamma = 1/2$, $\underline{\theta} = 2$, $\bar{\theta} = 10$, $\chi = 4/5$, $L = 10$, $p_E = 1$. Left-hand side: Tax schedules. Right-hand side: The agent's net-utility.

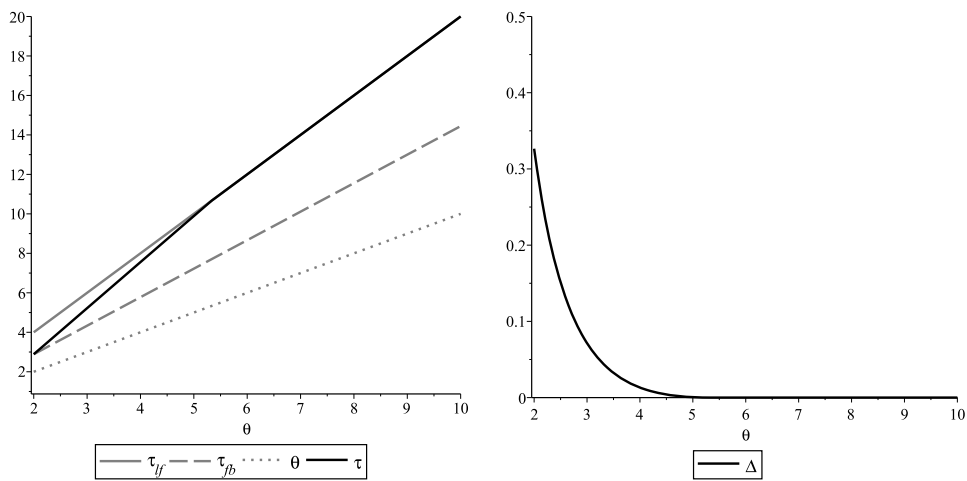


Figure 2: Illustration for $\gamma > 1$. Parameters: $\gamma = 2$, $\underline{\theta} = 2$, $\bar{\theta} = 10$, $\chi = 4/5$, $L = 10$, $p_E = 1$. Left-hand side: Tax schedules. Right-hand side: The agent's net-utility.

tively. The left-hand side figure illustrates the optimal contract tax schedule as a black and solid curve, compared to the laissez-faire tax, depicted as a gray and solid curve, the principal's preferred (Pigouvian) tax schedule as a gray dotted curve, and the first-best (symmetric-information) tax schedule as a gray dashed curve. The right-hand side figure illustrates the agent's information rent Δ . The agent earns an information rent with those θ that imply a deviation from his laissez-faire tax. There may be, however, an interval of θ realizations where the agent sets his own preferred tax and receives no rent (and thus, no reward).

Note that for $\gamma < 1$, the contract tax approaches the full-information tax for $\theta = \bar{\theta}$. For $\gamma > 1$, the tax approaches the full-information tax for $\theta = \underline{\theta}$. This matches the usual "no distortion at the top" result from standard principal-agent models. Thus, in each case there is one bound of the impact distribution for which the distortionary influence of the information friction on the tax vanishes, while the impact of the pure agency friction analyzed in Section 4 remains. The respective other bound of the distribution, even if there is no binding interval, leaves no information rent to the agent, but there the agent's preferred policy is implemented.

Both in the equilibrium tax paths in Proposition 1 and in the figures, we can illustrate how the pure agency friction from Section 4 and the additional asymmetric-information friction interact. If there were no agency friction, the tax would always be θ , which just internalizes the environmental externality when damage costs reflect the principal's preferences. With the need to delegate to a specialist bureaucrat, the tax is $\tau_{fb}(\theta)$, so the difference between the two tax levels is the pure agency friction. Proposition 1 shows that the additional information friction has two effects; in the θ region where the participation constraint is binding, the tax becomes $\gamma\theta$, and in the region where it is not binding, a term that depends on the distribution function is subtracted from (in the case of $\gamma < 1$) or added to (in the case of $\gamma > 1$). This directly represents the friction due to asymmetric information. In Figures 1 and 2, the difference between the dotted and the dashed gray curves represents the agency friction, and the dif-

ference between the dashed gray curve and the solid black curve represents the additional information friction. However, remember that this only describes the effects on the tax.

To give some intuition for the resulting equilibria, we will focus on the different cases in turn. For the situation in which the agency is less concerned about environmental damage than the government, $\gamma < 1$, the incentive problem is that the bureaucrat is inclined to understate the true impact, to make the government choose low regulation. To induce truth-telling, the government will therefore offer a contract such that stating high θ values yields an information rent. This enables the principal to implement a contract tax $\tau^*(\theta)$ which exceeds the tax that the agent would unilaterally choose.

If there exists some interior $\hat{\theta}$ for which the contract tax equals τ_{lf} , the participation constraint would then become binding. Incentive compatibility would require a further tax decrease resulting in a negative net-utility, hence violating the participation constraint. The principal is then forced to 'choose' the lowest possible tax which is then τ_{lf} making the participation constraint become binding for types $\theta \leq \hat{\theta}$.¹⁷

We now turn to the situation in which the agency is more environmentally concerned than the government, $\gamma > 1$, but cares little for monetary incentives (i.e., χ is large enough). In this situation, a very similar reasoning as before applies. Agents have an incentive to overstate the impact. Thus, net utility is smaller for higher- θ types. The contract tax $\tau^*(\theta)$ is lower than the one that the agent would unilaterally choose, and higher than the one preferred by the principal. For $\check{\theta}$, the contract tax equals τ_{lf} . From then on ($\theta > \check{\theta}$), the participation constraint is binding such that then $\tau^*(\theta) = \tau_{lf}(\theta)$. Increasing the transfer to avoid the participation constraint to become binding is again too costly to implement. This is, however, only true if the agent's valuation of the reward is low.

¹⁷Likewise, the principal could increase the transfer to induce a lower tax (hence avoiding the participation constraint to become binding). This, however, would require an increase in the information rent for all higher types. This is too costly for the principal.

In the case in which this valuation is high enough ($\chi < \frac{\gamma-1}{\gamma}$), the agents again have an incentive to overstate the true impact (because $\gamma > 1$ still), but the costs to avoid the participation constraint to become binding are reasonably low. Thus, the principal will offer a contract which only takes the incentive constraint into account except for the highest- θ type. All agents acquire an information rent (except for $\bar{\theta}$).

5.4 Comparative Static Results

Having derived the equilibrium policy, we turn to analyzing how parameter changes affect the tax structure. We analyze the influence of four parameters. Firstly, we consider the agent's environmental preference parameter γ , secondly, his responsiveness to monetary rewards (χ), thirdly and fourthly the expected value and standard deviation of the impact parameter θ .

Let us begin with γ .

Proposition 2 (Higher Valuation of Environmental Damage).

- i. Suppose that $\gamma < 1$. Then an increase in γ implies that the participation constraint binds for a larger region of the impact distribution (if it does for any). Within the binding region, the tax increases. Within the non-binding region, the tax increases for $\theta > \bar{\theta}/2$.
- ii. Suppose that $\gamma > 1$. Then an increase in γ implies that the participation constraint binds for a smaller region of the impact distribution (if it does for any). Both within the binding and the non-binding region, the tax increases.

Proof. Differentiate the equilibrium tax schedules given in Proposition 1 and the cutoff type values. □

A change in γ affects the incentive-compatibility constraint in two different ways. On the one hand, an increase in γ makes the outside option less valuable for any θ because a higher- γ agent will always experience a stronger (negative) impact. This decreases the incentive to understate the impact. On the other hand,

the stronger disutility of θ due to the higher γ is also felt within the contract. Thus, the overstating incentive is enforced.

In isolation, the latter effect would call for an increase in the equilibrium tax, because $\Delta'(\theta)$ is decreasing in γ . An increase in τ then 'flattens' the net-utility schedule which is valuable for the principal (as argued in detail in Appendix A.2). In general, with both effects at work, it is ambiguous whether $\Delta'(\theta)$ is increasing or decreasing in γ . Thus, the optimal reaction of the principal is ambiguous as well.

For the $\gamma < 1$ types, an increase of γ implies that the regulator's preferences become more similar to those of the government. Firstly, this should imply that the government can accept a larger range of the θ distribution for which the agent can choose his laissez-faire policy. Secondly, for the θ values that are included in the contract, the compromise tax is higher due to the less severe conflict of interest. At least for high θ , this outweighs the fact that the principal can save rewards by lowering taxes. Moreover, with $\gamma \rightarrow 1$, the cut-off value moves to $\bar{\theta}$, so the inequality holds for all remaining non-binding θ .

For the $\gamma > 1$ types, an increase in γ makes the conflict of interest *stronger*, so the opposite is true. Because the regulator's laissez-faire tax is farther and farther away from that of the principal, the binding region becomes smaller in order to reach a compromise for more impact realizations. The principal has to concede rewards to more types, but the increase in the conflict of interest directly refers to policy, while the principal's marginal disutility of paying rewards remains the same. Thus, in the new equilibrium the principal is willing to pay more to equalize marginal effects.

Let us now turn to the effect of a change in the agent's reward valuation.

Proposition 3. *An increase in the parameter χ implies a reduction of the agent's valuation ζ of the monetary transfer r . Such an increase of χ increases (decreases) the equilibrium tax $\tau^*(\theta)$ over the non-binding interval for $\gamma > (<)1$. For the θ values for which the participation constraint is binding (initially and after the marginal*

change), the equilibrium tax remains unaffected. However, for both $\gamma > 1$ and $\gamma < 1$, the binding region becomes larger.

Proof. Consider the tax schedule for $\gamma > 1$ over the non-binding interval

$$\frac{\partial \tau^*(\theta)}{\partial \chi} = \frac{(2\gamma - 1)\theta - \underline{\theta}}{(1 + \chi)^2} > 0. \quad (41)$$

Note that (41) is positive for $\theta = \underline{\theta}$, hence it is positive $\forall \theta$. Now consider the tax schedule for $\gamma < 1$ over the non-binding interval

$$\frac{\partial \tau^*(\theta)}{\partial \chi} = \frac{(2\gamma - 1)\theta - \bar{\theta}}{(1 + \chi)^2} < 0. \quad (42)$$

Note that (42) is negative for $\theta = \bar{\theta}$, hence it is negative $\forall \theta$. For the last sentence, differentiate the cutoff values. \square

Consider an increase in χ , i.e., the agent's valuation of a monetary transfer decreases. We first focus on the case of $\gamma > 1$. Initially, the principal chooses a tax such that the marginal utility loss of a tax increase for one θ -realization type (the principal strictly prefers a lower tax than the agent) balances savings on information rent for all possible θ types. The marginal utility loss is decreasing in χ (since a tax increase saves a large chunk on monetary transfers) and the savings on information rents are increasing. Thus, the optimal reaction is to increase the tax.

With $\gamma < 1$, a similar reasoning applies. The marginal utility gain then is decreasing, and the rents that have to be paid to the agents to ensure truth-telling increase (at the margin). The optimal reaction then is to decrease the tax.

Intuitively, if the regulator values the reward lower, it becomes more expensive to compensate him for forgoing his preferred policy. Therefore, the government will attempt less to do so, and in effect exclude more types from the contract. With less and less reward valuation, there are less and less impact realizations for which the government chooses to influence policy. However, the “no

distortion at the top (bottom)” for $\gamma < 1$ ($\gamma > 1$) still holds.

We now turn to the effects of changes in the moments of the distribution function. To this end, note that with a uniform distribution we can write

$$\underline{\theta} = \mathbb{E}(\theta) - \sqrt{3}\sigma, \quad (43)$$

$$\bar{\theta} = \mathbb{E}(\theta) + \sqrt{3}\sigma. \quad (44)$$

This allows us to separately discuss changes if either the expected impact $\mathbb{E}(\theta)$ changes, or the standard deviation σ of the damage changes (i.e., there is a mean-preserving spread). We start by discussing the effect of an increase of the expected impact. Note for further reference that the probability of θ realization in the binding region (for $\gamma < 1$) is

$$\frac{\hat{\theta} - \underline{\theta}}{\bar{\theta} - \underline{\theta}} = \frac{\left(\frac{\chi}{\chi - \frac{\gamma-1}{\gamma}} - 1\right) \mathbb{E}(\theta) + \left(\frac{\chi}{\chi - \frac{\gamma-1}{\gamma}} + 1\right) \sqrt{3}\sigma}{2\sqrt{3}\sigma} \quad (45a)$$

For $\gamma > 1$, it is

$$\frac{\bar{\theta} - \check{\theta}}{\bar{\theta} - \underline{\theta}} = \frac{\left(1 - \frac{\chi}{\chi - \frac{\gamma-1}{\gamma}}\right) \mathbb{E}(\theta) + \left(1 + \frac{\chi}{\chi - \frac{\gamma-1}{\gamma}}\right) \sqrt{3}\sigma}{2\sqrt{3}\sigma}, \quad (45b)$$

given that $\chi - (\gamma - 1)/\gamma > 0$, so that a binding region can exist.

Proposition 4. *An increase in the expected impact $\mathbb{E}(\theta)$ decreases $\tau^*(\theta)$ over a non-binding interval, irrespective of the agents' environmental preference parameter γ . $\hat{\theta}$ and $\check{\theta}$ increase, but the share of binding θ values becomes smaller.*

Proof. The first part of the proposition is proven by plugging (43) and (44) into the equilibrium relations from Proposition 1 and differentiating. The second part is proven by differentiating the cutoff values and differentiating (45). \square

An increase in $\mathbb{E}(\theta)$ with an unchanged σ implies a shift of the impact distribution to the right. We first turn to the case of $\gamma < 1$. Note that with the change in $\mathbb{E}(\theta)$, it must still hold for the tax that there is no distortion at the top (hence at

the 'new' $\bar{\theta}$). Moreover, $\hat{\theta}$ increases, so that the low laissez-faire tax is chosen for a higher θ than before the change. Thus, the tax at the end of the binding interval as well as the tax at $\bar{\theta}$ increase. Consequently, the non-binding tax schedule shifts to the right, implying lower taxes for any θ over the non-binding interval. The economic intuition is that with a shift in the damage distribution the government c.p. has to concede more information rents to the regulatory agency. It is then, however, optimal to save on this by offering a (for the agent) more favorable tax schedule which implies a tax decrease.

For $\gamma < 1$, a very similar reasoning holds true. The tax at the start of the binding interval as well as the (non-distortive) tax at $\underline{\theta}$ increase. Again, the tax schedule shifts to the right implying a tax decrease. The economic intuition behind this result is, however, somewhat different. Now with a shift of the damage distribution, the government saves, ceteris paribus, on the information rent that it has to concede to the agent. This enables the government to implement a higher tax schedule.

We next consider the effect of a mean-preserving spread.

Proposition 5. *An increase in the standard deviation σ – that is, a mean-preserving spread of the impact – decreases (increases) $\tau^*(\theta)$ over a non-binding interval for $\gamma < (>)1$. $\hat{\theta}$ increases, $\check{\theta}$ decreases, but the share of binding θ values is unaffected.*

Proof. The first part of the proposition is proven by plugging (43) and (44) into the equilibrium relations from Proposition 1 and differentiating. The second part is proven by differentiating the cutoff values and differentiating (45). \square

'Spreading out' the impact distribution implies that for the case of $\gamma < 1$ a tax decrease implies savings on the rents for all high- θ types (under incentive compatibility). Thus, although the tax decrease implies a direct utility loss, the optimal reaction is to decrease the tax. The same logic applies to $\gamma > 1$. In this case a tax increase decreases the rents that have to be paid to ensure truth-telling. Again, the direct utility loss due to the tax increase is unaffected. Then, the optimal reaction is to increase the tax.

Intuitively, a higher standard deviation increases the uncertainty from the principal's point of view, so the information asymmetry is higher. This implies that the agent should receive a higher information rent, which will partly come in the form of a tax nearer to the one he prefers, and partly in the form of reward payments.

Our results help to understand different policy reaction to different kinds of environmental damage. First of all, we should observe differences between the regulation of different pollutants, depending on the uncertainty about their impact *before* environmental agencies analyze it in depth. For example, if a government in some country considers to allow hydraulic fracturing and it has heard diverging or even contradictory accounts of how dangerous this may be for drinking water reservoirs, regulatory bureaus should have a large influence on regulation. However, if experience from other countries has already narrowed down the range of possible environmental damages, the agency's influence should be smaller.

By the same token our results shed some light on how to think about implementing new technologies that supposedly have negative externalities which require a specialized regulatory agency for internalization. In contrast to the Pigouvian framework (based, e.g., on some expected marginal damage), we show that an additional cost has to be taken into account. The informational friction increases the need to concede rents, the higher the uncertainty. Accordingly, welfare judgments that ignore this informational friction may be highly misleading.

Moreover, there are cases where regulation means indeed repeatedly drawing from some distribution. Even though our example in the model was environmental taxation, consider a setting where a similar logic might be at work: Safety regulation of oil platforms. If inspectors are, as it has been conjectured (cf. Muehlenbachs et al., 2013), biased in favor of either the firms owning the platforms or the staff, we would expect sanctions to be too soft, except for the most severe safety problems. Inspectors should receive some reward for report-

ing severe problems. Moreover, consider an event like Hurricane Katrina in 2005, which badly damaged oil platforms in the Gulf of Mexico. After such an event, it may be very unclear how much a single platform has been hit, implying an increase in uncertainty, leading to more leeway for the inspectors.

6 Conclusion

In this paper, we characterize and analyze the equilibrium environmental tax in an economy where a principal (the government) has to assign the task of setting this tax to an environmental agency. We argue that the need of an agency to set the tax stems from the fact that judging environmental impact is an expert's task. This need, however, gives rise to an adverse-selection problem. With the agency having superior knowledge concerning the environmental impact of the regulated activity, and with diverging preferences for internalizing environmental externalities, it has an incentive to misrepresent the true environmental impact.

We then characterize the equilibrium contract (tax demands by the principal and transfer payments to the agent) that induces truth-telling. In our setting this is a demanding task, because with the agent having discretionary power over setting the tax, the value of not participating in the contract is type-dependent. This gives rise to countervailing incentives (first analyzed by Lewis and Sappington, 1989).

Irrespective of their attitude towards the environmental damage, agents have an incentive to overstate the impact to improve their situation within the contract. Then again, agents have a countervailing incentive to understate the impact to signal a highly-valued outside option. Using results from Maggi and Rodríguez-Clare, 1995, we are able to characterize the equilibrium.

We show that in equilibrium the tax exceeds (falls short of) the full-information tax if the agency is more (less) environmentally concerned than the principal. In any case, the tax is increasing in the impact θ (as it would be under

full information). We show that for a more (less) environmentally concerned agency the generic (countervailing) overstating (understating) incentive dominates throughout. As such, we have no distortion for the lowest (highest) impact. Moreover, we show that the participation constraint (i.e., the constraint that the agents' net-utility must not be negative) may be binding on a non-degenerate 'corner' interval.

Equipped with the equilibrium tax relation, we discuss comparative static effects. One point we derive is that a more policy-oriented agent (which means that the valuation of monetary rewards is low) has more leeway in setting the tax. Consequently, the tax increases (decreases) for more (less) environmentally concerned agents when they are more policy-oriented. A second point is that a mean-preserving spread in the impact distribution implies a higher (lower) tax for more (less) environmentally concerned agents. This helps to understand different policy reactions to different kinds of environmental damage.

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A Appendix

A.1 Characteristics of Incentive-Compatible Contracts

Along with the first-order condition (29), the second-order condition

$$\frac{\partial^2 v(\theta, \theta')}{\partial \theta'^2} \leq 0 \quad (\text{A.1})$$

must be fulfilled in optimum. Differentiating (29), we see that for any incentive-compatible (or “truthful”) contract,

$$\frac{\partial^2 v(\theta, \theta')}{\partial \theta'^2} \cdot d\theta + \frac{\partial^2 v(\theta, \theta')}{\partial \theta \partial \theta'} \cdot d\theta = 0. \quad (\text{A.2})$$

Substituting this in (A.1) yields

$$\frac{\partial^2 v(\theta, \theta')}{\partial \theta \partial \theta'} \geq 0. \quad (\text{A.3})$$

Differentiating (28) yields

$$\frac{\partial^2 v(\theta, \theta')}{\partial \theta \partial \theta'} = 2 \cdot \gamma \cdot (p_E + \tau(\theta'))^{-3} \cdot L \cdot \tau'(\theta') \quad (\text{A.4})$$

Thus, if we assume that the gross energy price is positive (otherwise the economy will not have a meaningful equilibrium anyway), the tax of an incentive-compatible contract must be non-decreasing in θ to fulfill (A.3). On a more basic level, $\frac{\partial^2 w}{\partial r \partial \theta}$ has the same sign globally (the *Spence-Mirrlees condition* is fulfilled) and as it is positive, the tax has to increase in θ' . For all this, cf. Fudenberg and Tirole (1991), Section 7.3.

A.2 Applying Optimal Control Theory with Pure State Constraints to the Principal-Agent Problem

To maximize (34) subject to the incentive-compatibility constraint (31), form the Hamiltonian

$$\mathcal{H}(\theta, \tau, \Delta, \lambda) = f(\theta) \cdot u(\theta, \tau, \Delta) + \lambda \cdot [\rho(\tau) - \omega_{lf}'(\theta)], \quad (\text{A.5})$$

where

$$u(\theta, \tau, \Delta) := \left[\frac{1 + \chi}{p_E + \tau} + \frac{\tau - \theta + \chi \cdot (\tau - \gamma \cdot \theta)}{(p_E + \tau)^2} \right] \cdot L - \chi \cdot \omega_{lf} - \chi \cdot \Delta \quad (\text{A.6})$$

$$\rho(\tau) := -\frac{\gamma L}{(p_E + \tau)^2} \quad (\text{A.7})$$

by (31). Thus, the incentive compatibility is implemented as an equation of motion of the information rent between θ types. To also take the participation constraint (32) into account, we use a Kuhn-Tucker inequality constraint.¹⁸ The Lagrangian is

$$\mathcal{L}(\theta, \tau, \Delta, \lambda, \mu) = \mathcal{H}(\theta, \tau, \Delta, \lambda) + \mu \cdot \Delta(\theta). \quad (\text{A.8})$$

¹⁸For a thorough explanation and discussion of the use of pure state constraints like this in optimal-control theory, see, e.g., Seierstad and Sydsæter (1987, chapter 5), Kamien and Schwartz (1991, section 17), Feichtinger and Hartl (1986), or Hartl et al. (1995).

The first-order condition for the control variable τ is $\partial\mathcal{L}/\partial\tau = 0$, which is

$$f(\theta) \cdot \frac{\partial u(\theta, \tau(\theta), \Delta(\theta))}{\partial\tau} + \lambda(\theta) \cdot \rho'(\tau(\theta)) = 0. \quad (\text{A.9})$$

The equations of motion of the costate and of the agent's utility must fulfill $\lambda'(\theta) = -\partial\mathcal{L}/\partial\Delta$ and $\Delta'(\theta) = \partial\mathcal{L}/\partial\lambda$, respectively, which yields

$$\lambda'(\theta) = \chi \cdot f(\theta) - \mu(\theta), \quad (\text{A.10})$$

$$\Delta'(\theta) = \rho(\tau(\theta)) - \omega_{lf}'(\theta), \quad (\text{A.11})$$

and the Kuhn-Tucker conditions are

$$\frac{\partial\mathcal{L}}{\partial\mu} = \Delta(\theta) \geq 0, \quad (\text{A.12a})$$

$$\mu(\theta) \geq 0, \quad (\text{A.12b})$$

$$\mu(\theta) \cdot \frac{\partial\mathcal{L}}{\partial\mu} = 0. \quad (\text{A.12c})$$

Finally, because utility at both endpoints can be chosen by the principal (subject to the participation constraint), we have the following transversality conditions:

$$\lambda(\underline{\theta}) = 0, \quad (\text{A.13a})$$

$$\lambda(\bar{\theta}) = 0. \quad (\text{A.13b})$$

The costate value may jump downwards where the Kuhn-Tucker constraint is active. For any such jump-point θ_j , it must hold that¹⁹

$$\lambda(\theta_j^-) = \lambda(\theta_j^+) + \eta(\theta_j), \quad (\text{A.14a})$$

$$\eta(\theta_j) \geq 0, \quad (\text{A.14b})$$

$$\eta(\theta_j) \cdot \Delta(\theta) = 0, \quad (\text{A.14c})$$

¹⁹Cf. Feichtinger and Hartl (1986, section 6.2).

where we denote by $\lambda(\theta_j^-)$ ($\lambda(\theta_j^+)$) the left (right) limit of λ at θ .

The interpretation of “dynamic” optimality (between types) and, in particular, the interpretation of the costate λ can be a bit tricky and little intuitive (cf. Kaplow, 2010). Therefore we start with a contentual interpretation of the last summand of (A.5). By (A.11), it is equivalent to $\lambda \cdot \Delta'(\theta)$.

Suppose $\Delta'(\theta) > 0$. Then the lowest- θ type in the range we are considering receives the lowest rent. Each higher- θ type receives a higher information rent for not claiming a lower θ . With a larger $\Delta'(\theta)$, this “rent wedge” would increase, which would be bad for the principal. Thus, λ must be negative for $\Delta'(\theta) > 0$. It measures the effect of $\Delta'(\theta)$ (the Δ growth of type θ) on the principal’s expected utility (over all types).

Consider the reversed argument for $\Delta'(\theta) < 0$, implying that types with a lower θ receive an information rent. Now, the rent wedge would be smaller if the slope of Δ were less negative: The highest- θ type would still receive his minimum rent, and the rent of those with a lower θ would be reduced. Thus, because increasing $\Delta'(\theta)$ would be good for the principal, λ must be positive.

Next, consider the first-order condition (A.9). The first summand is the marginal surplus of τ . Suppose for a moment that this were the only summand. Then the principal would choose a marginal surplus of zero. This tax, τ_{fb} from the symmetric-information case (24), would maximize his utility subject to the restriction that he has to pay the agent for leaving his bliss-point tax.

The second summand reflects that the tax of one θ type has an impact on the incentive-compatible contracts of all other θ types, by changing $\rho(\tau(\theta))$ and, thus, $\Delta'(\theta)$. Differentiating (A.7) yields a positive term ($\rho'(\tau) > 0$).

By the discussion above, we know that λ is positive if $\Delta'(\theta) < 0$. Then, marginally raising the tax for some θ implies a (locally) flatter rent schedule, so that *less* rents have to be conceded to low- θ types. Put differently, raising $\tau(\theta)$ reduces the incentive to claim $\theta' > \theta$, and reducing this incentive allows to reduce payments, which is valuable for the principal. Here, $\lambda > 0$ stands for the principal’s value of the rent that would be saved at the margin over all types by

increasing $\tau(\theta)$ a bit further. For the first-order condition to hold, we then need $\partial u/\partial \tau < 0$, which means that the tax is higher than the surplus-maximizing one. (We would expect this to be true for $\gamma > 1$, because environmentally concerned agents have an incentive to trick the principal into setting a high tax, and we will in the following derive that this is indeed true.)

Now consider a situation where $\Delta'(\theta) > 0$ and $\lambda(\theta) < 0$. We still have $\rho'(\tau) > 0$, so marginally raising τ would increase the rents that the principal has to concede to the agent. (But this implies that decreasing $\tau(\theta)$ reduces them.) $\lambda(\theta) < 0$ reflects the principal's value of the rent that would be lost over all types by marginally increasing $\tau(\theta)$ (and the rent saved by reducing it). For the first-order condition to hold, we then need $\partial u/\partial \tau > 0$, which implies that the tax is lower than the surplus-maximizing one. (Along the same lines as in the $\Delta'(\theta) < 0$ case, we would expect this for $\gamma < 1$ types).

For concreteness, substituting and rearranging in (A.9) yields:

$$\begin{aligned}\tau(\theta) &= \frac{1 + \gamma \cdot \chi}{1 + \chi} \cdot \theta + \frac{1}{f(\theta)} \cdot \frac{\gamma}{1 + \chi} \cdot \lambda(\theta) \\ &= \tau_{lf}(\theta) + \frac{1 - \gamma}{1 + \chi} \cdot \theta + \frac{1}{f(\theta)} \cdot \frac{\gamma}{1 + \chi} \cdot \lambda(\theta) \\ &= \tau_{fb}(\theta) + \frac{1}{f(\theta)} \cdot \frac{\gamma}{1 + \chi} \cdot \lambda(\theta),\end{aligned}\tag{A.9'}$$

where $\tau_{lf}(\theta)$ is the laissez-faire tax from equation (16) and $\tau_{fb}(\theta)$ is the first-best tax level chosen under information symmetry from (24).

In the derivation of equilibrium, we make use of the following Lemma.²⁰

Lemma A.1 (Continuity). *The regularity conditions in this problem imply that the control variable $\tau(\theta)$ is continuous. Thus, by (A.9'), $\lambda(\theta)$ must be continuous as well except at the endpoints, where jumps obeying the conditions in (A.14) may occur.*

This lemma follows from the characteristics of optimal-control problems, cf. Feichtinger and Hartl (1986, section 6.2). Using it, we can integrate (A.10),

²⁰Cf. Feichtinger and Hartl (1986, section 6.2).

which yields

$$\begin{aligned}\lambda(\theta) &= \chi \cdot \left[F(\theta) - \underbrace{F(\underline{\theta})}_{=0} \right] - \int_{\underline{\theta}}^{\theta} \mu(\tilde{\theta}) d\tilde{\theta} + \lambda(\underline{\theta}^+) \\ &= \chi \cdot F(\theta) - \int_{\underline{\theta}}^{\theta} \mu(\tilde{\theta}) \cdot d\tilde{\theta} + \lambda(\underline{\theta}^+)\end{aligned}\quad (\text{A.15a})$$

for $\theta \in (\underline{\theta}, \bar{\theta})$. If there is no jump in λ at $\underline{\theta}$, $\lambda(\underline{\theta}^+) = 0$. If there is a downward jump, $\lambda(\underline{\theta}^+) < 0$. Equivalently, we can integrate from the upper bound and write

$$\begin{aligned}\lambda(\theta) &= \chi \cdot \left[F(\theta) - \underbrace{F(\bar{\theta})}_{=1} \right] + \int_{\theta}^{\bar{\theta}} \mu(\tilde{\theta}) d\tilde{\theta} + \lambda(\bar{\theta}^-) \\ &= \chi \cdot [F(\theta) - 1] + \int_{\theta}^{\bar{\theta}} \mu(\tilde{\theta}) d\tilde{\theta} + \lambda(\bar{\theta}^-).\end{aligned}\quad (\text{A.15b})$$

If there is no jump in λ at $\bar{\theta}$, $\lambda(\bar{\theta}^-) = 0$. If there is a downward jump, $\lambda(\bar{\theta}^-) > 0$.

Having laid out the optimality conditions in general, we now explicitly derive optimal contracts that take both understating and overstating incentives into account.²¹ To derive unambiguous propositions, we focus on cases in which the damage is uniformly distributed, i.e., we assume:

Assumption A.1 (Uniform Distribution). *The distribution function of the damage is given by $F(\theta) = f(\theta)(\theta - \underline{\theta})$, where $f(\theta)$ is the density $f(\theta) = \frac{1}{\bar{\theta} - \underline{\theta}}$.*

Now we characterize the behavior of variables depending on the behavior of $\Delta'(\theta)$. First consider which conditions must be fulfilled if the rent is to remain constant.

Lemma A.2 (Constant rent). *Consider some $\theta = \theta_0$ for which $\Delta'(\theta_0) = 0$. Then:*

$$\tau(\theta_0) = \tau_{lf}(\theta_0) \equiv \gamma\theta_0, \quad (\text{A.16})$$

$$\lambda(\theta_0) = \lambda_0(\theta_0) := \frac{\gamma - 1}{\gamma} \theta_0 f(\theta_0). \quad (\text{A.17})$$

²¹This is a special case of the general discussion of principal-agent problems with countervailing incentives of Maggi and Rodríguez-Clare (1995).

Proof. $\Delta'(\theta) = 0$ implies, by (A.11), $\rho(\tau(\theta)) = \omega_{lf}'(\theta)$. From the respective definitions, (A.7) and (18), this implies (A.16). Substituting in (A.9') then implies (A.17). \square

Extending this to an interval yields additional insights:

Lemma A.3 (Constant-rent interval). *Consider an interval $\theta \in [\theta_0, \theta_1]$, where $\Delta'(\theta) = 0 \forall \theta \in [\theta_0, \theta_1]$. Then for $\theta \in [\theta_0, \theta_1]$ it must hold that:*

$$\lambda'(\theta) = \lambda'_0(\theta) := \frac{\gamma - 1}{\gamma} f(\theta), \quad (\text{A.18})$$

$$\mu(\theta) = \left[\chi - \frac{\gamma - 1}{\gamma} \right] f(\theta), \quad (\text{A.19})$$

and an optimal contract can only contain a $\Delta'(\theta) = 0$ interval if

$$\chi - \frac{\gamma - 1}{\gamma} \geq 0. \quad (\text{A.20})$$

If (A.20) holds as a strict inequality,

$$\Delta'(\theta) = 0 \Rightarrow \Delta(\theta) = 0 \quad (\text{A.21})$$

on the interval.

Proof. By Lemma (A.2), $\lambda(\theta) = \lambda_0(\theta)$ on the interval. Differentiating $\lambda_0(\theta)$ and taking Assumption A.1 into account yields (A.18). Substituting this in the costate equation of motion (A.10) yields (A.19). Finally, the Kuhn-Tucker condition (A.12) requires $\mu(\theta) \geq 0$. If (A.20) holds as a strict inequality, (A.12c) implies (A.21). \square

Over any binding interval, $\Delta'(\theta) = 0$ by definition, so that all results from Lemma A.3 apply there. Additionally, (A.21) tells us that any interval with constant rent must be a binding interval (except if (A.20) holds as an equality).

Now we consider the two cases where the rent is not constant.

Lemma A.4 (Increasing rent). *Consider an interval $\theta \in [\theta_2, \theta_3]$ for which $\Delta'(\theta) > 0$. Then the following relations hold over this interval:*

$$\Delta(\theta_2) \geq 0, \quad (\text{A.22})$$

$$\Delta(\theta) > 0 \quad \forall \theta \in (\theta_2, \theta_3], \quad (\text{A.23})$$

$$\mu(\theta) = 0 \quad \forall \theta \in (\theta_2, \theta_3], \quad (\text{A.24})$$

$$\lambda'(\theta) = \chi \cdot f(\theta) \quad \forall \theta \in (\theta_2, \theta_3], \quad (\text{A.25})$$

and

$$\tau(\theta) > \tau_{lf}(\theta) \equiv \gamma\theta, \quad (\text{A.26})$$

$$\lambda(\theta) > \lambda_0(\theta) \quad (\text{A.27})$$

for $\theta \in [\theta_2, \theta_3]$.

Proof. (A.22) follows from the participation constraint. By $\Delta'(\theta) > 0$, $\Delta(\theta) > \Delta(\theta_2)$ for $\theta > \theta_2$, implying (A.23). $\Delta(\theta) > 0$ implies (A.24) by the Kuhn-Tucker condition (A.12c). Substituting $\mu(\theta) = 0$ in the costate equation of motion (A.10) yields (A.25).

$\Delta'(\theta) > 0$ implies, by (A.11), $\rho(\tau(\theta)) > \omega_{lf}'(\theta)$. From the respective definitions, (A.7) and (18), this implies (A.26). Substituting in (A.9') then implies (A.27). \square

From the inequality (A.27), we can determine a condition where $\Delta'(\theta) > 0$ for some θ implies $\Delta'(\theta) > 0$ as well for any larger θ :

Lemma A.5 (Increasing-rent interval bounded by $\bar{\theta}$). *Suppose there is an interval $\theta \in [\theta_2, \theta_3]$ for which $\Delta'(\theta) > 0$, as in Lemma A.4. If (A.20) is fulfilled ($\chi - \frac{\gamma-1}{\gamma} \geq 0$), we must have $\Delta'(\theta) > 0$ for all $\theta \geq \theta_2$ (sufficient condition).*

Proof. If

$$\lambda'(\theta) \geq \lambda'_0(\theta) \quad (\text{A.28})$$

holds over the interval, the rent must unambiguously be increasing for any higher θ because (A.27) must hold to the right of any θ . Thus, we can always extend the interval to any higher θ (up to $\bar{\theta}$), and the conditions from Lemma A.4 still hold. Because $\Delta(\theta) > 0$ over the interval, $\lambda'(\theta) = \chi f(\theta)$ by (A.10). Substituting this and $\lambda'_0(\theta)$ into (A.28) and simplifying yields (A.20). \square

By the same token, we have the reversed case:

Lemma A.6 (Decreasing rent). *Consider an interval $\theta \in [\theta_4, \theta_5]$ for which $\Delta'(\theta) < 0$. Then the following relations hold over this interval:*

$$\Delta(\theta_5) \geq 0, \quad (\text{A.29})$$

$$\Delta(\theta) > 0 \quad \forall \theta \in [\theta_4, \theta_5), \quad (\text{A.30})$$

$$\mu(\theta) = 0 \quad \forall \theta \in [\theta_4, \theta_5), \quad (\text{A.31})$$

$$\lambda'(\theta) = \chi \cdot f(\theta) \quad \forall \theta \in [\theta_4, \theta_5), \quad (\text{A.32})$$

and

$$\tau(\theta) < \tau_{lf}(\theta) \equiv \gamma\theta, \quad (\text{A.33})$$

$$\lambda(\theta) < \lambda_0(\theta) \quad (\text{A.34})$$

for $\theta \in [\theta_4, \theta_5]$.

Proof. (A.29) follows from the participation constraint. By $\Delta'(\theta) < 0$, $\Delta(\theta) > \Delta(\theta_5)$ for $\theta < \theta_5$, implying (A.30). The rest follows from the proof of Lemma A.4. \square

Lemma A.7 (Decreasing-rent interval bounded by θ). *Suppose there is an interval $\theta \in [\theta_4, \theta_5]$ for which $\Delta'(\theta) < 0$, as in Lemma A.6. If (A.20) is fulfilled, $\chi - \frac{\gamma-1}{\gamma} \geq 0$,*

we must have $\Delta'(\theta) < 0$ for all $\theta \leq \theta_5$ (sufficient condition).

Proof. If (A.28) holds over the interval, the rent must unambiguously be decreasing for any lower θ because (A.34) must hold to the left of any θ on the interval. Thus, we can always extend the interval to any lower θ (down to $\underline{\theta}$), and the conditions from Lemma A.6 still hold. The rest follows from the proof of Lemma A.5. \square

We start the derivation of optimal contracts by noting a kind of contract that can never be optimal:

Proposition A.1 (No waste). *There is at least one $\theta \in [\underline{\theta}, \bar{\theta}]$ for which (A.12a) holds as an equality.*

Proof. We prove by contradiction. Suppose that $\Delta(\theta) > 0 \forall \theta$. Then by (A.12), $\mu(\theta) = 0 \forall \theta$. By (A.14), λ cannot jump. Thus by (A.15a), $\lambda(\theta) = \chi \cdot F(\theta)$, implying $\lambda(\bar{\theta}) = \chi$, which contradicts the transversality condition (A.13). \square

The intuition for this is simple: If the agent had the participation constraint more than fulfilled for each θ , the principal could reduce transfers for at least one type. Thus, a contract cannot be optimal if the constraint never binds.

Additionally, there is one valid case which we can discuss very briefly:

Proposition A.2 (Participation constraint binding globally). *Suppose that the participation constraint is binding over the whole range: $\Delta(\theta) = 0 \forall \theta$. Then it must be true that $\gamma = 1$.*

Proof. Substituting $\mu(\theta)$ from Lemma A.3 into (A.15a) and evaluating at $\bar{\theta}$ yields:

$$\lambda(\bar{\theta}) = \frac{\gamma - 1}{\gamma} + \lambda(\underline{\theta}^+). \quad (\text{A.35})$$

With (A.13), this implies $\lambda(\underline{\theta}^+) = \frac{1-\gamma}{\gamma}$. Substituting $\mu(\theta)$ from Lemma A.3 into (A.15b) and evaluating at $\underline{\theta}$ yields:

$$\lambda(\underline{\theta}) = -\frac{\gamma - 1}{\gamma} + \lambda(\bar{\theta}^-). \quad (\text{A.36})$$

With (A.13), this implies $\lambda(\bar{\theta}^-) = \frac{\gamma-1}{\gamma}$. Thus, either $\gamma = 1$, or we would need two jumps in opposite directions, which is impossible by (A.14). \square

With $\gamma = 1$, the agent's interests perfectly coincide with the principal's. Therefore, the agency problem dissolves, and so does the information rent, and the payment can be zero for every θ .

Proposition A.3 ($\gamma < 1$ implies that high- θ types receive a rent). *Suppose that $\gamma < 1$. Then one of the following two cases holds.*

1. $\Delta'(\theta) > 0$ for $\theta \in [\underline{\theta}, \bar{\theta}]$, implying $\Delta(\underline{\theta}) = 0$, $\Delta(\theta) > 0$ for $\theta \in (\underline{\theta}, \bar{\theta}]$ by Lemma A.4 and Proposition A.1.
2. There is some $\hat{\theta} \in (\underline{\theta}, \bar{\theta}]$ such that $\mu(\theta) > 0$, $\Delta(\theta) = 0 \forall \theta \in [\underline{\theta}, \hat{\theta}]$ and $\Delta'(\theta) > 0 \forall \theta \in (\hat{\theta}, \bar{\theta}]$, implying $\Delta(\hat{\theta}) = 0$, $\Delta(\theta) > 0$ for $\theta \in (\hat{\theta}, \bar{\theta}]$ by Lemma A.4 and Proposition A.1.

Proof. We prove by contradiction. Firstly, note that by $\gamma < 1$, (A.20) holds as a strict inequality. Thus, if there were any θ for which $\Delta'(\theta) < 0$, then $\Delta'(\underline{\theta}) < 0$ and $\Delta(\underline{\theta}) > 0$ would necessarily have to hold by Lemma A.7. By $\Delta(\underline{\theta}) > 0$, $\lambda(\underline{\theta}^+) = \lambda(\underline{\theta}) = 0$ in (A.15a). Substituting this in the $\Delta'(\theta) < 0$ condition (A.34) yields

$$0 < \lambda_0(\underline{\theta}) = \frac{\gamma-1}{\gamma} \underline{\theta} f(\underline{\theta}), \quad (\text{A.37})$$

which contradicts $\gamma < 1$. Secondly, by Proposition A.2, $\Delta(\theta) = 0$ cannot hold globally. Thus, there must be some θ for which $\Delta(\theta) > 0$, leaving only the solutions described above. \square

Let us now derive the tax path for $\gamma < 1$. For the interval $[\hat{\theta}, \bar{\theta}]$, we have

$$\lambda(\theta) = \chi \cdot [F(\theta) - 1] \quad (\text{A.38})$$

by (A.15b). For the interval $[\underline{\theta}, \hat{\theta}]$, $\lambda(\theta) = \lambda_0(\theta)$ by Lemma A.2. Thus, $\hat{\theta}$, which separates the binding from the non-binding interval, is defined by $\lambda_0(\hat{\theta}) = \chi \cdot$

$[F(\hat{\theta}) - 1]$, which yields:

$$\hat{\theta} = \frac{\chi}{\chi - \frac{\gamma-1}{\gamma}} \bar{\theta}. \quad (\text{A.39})$$

If $\hat{\theta} \leq \underline{\theta}$, there is no binding interval, and $\Delta'(\theta) > 0$ globally. Substituting $\lambda(\theta) = \chi [F(\theta) - 1]$ (and Assumption A.1) in (A.9') and using Lemma A.2, the optimal tax schedule is

$$\tau^*(\theta) = \begin{cases} \gamma\theta & \forall \theta \leq \hat{\theta}, \\ \frac{1+\gamma\chi}{1+\chi} \cdot \theta - \frac{\gamma\chi}{1+\chi} \cdot (\bar{\theta} - \theta) & \forall \theta \geq \hat{\theta}. \end{cases} \quad (\text{A.40})$$

Now let us turn to an agent who is more environmentalist than the principal.

Proposition A.4 ($\gamma > 1$ implies that low- θ types receive a rent). *Suppose that $\gamma > 1$. Then one of the following two cases holds.*

1. $\Delta'(\theta) < 0$ for $\theta \in [\underline{\theta}, \bar{\theta}]$, implying $\Delta(\bar{\theta}) = 0$, $\Delta(\theta) > 0$ for $\theta \in [\underline{\theta}, \bar{\theta})$ by Lemma A.6 and Proposition A.1.
2. There is some $\check{\theta} \in [\underline{\theta}, \bar{\theta})$ such that $\mu(\theta) > 0$, $\Delta(\theta) = 0 \forall \theta \in [\check{\theta}, \bar{\theta}]$ and $\Delta'(\theta) < 0 \forall \theta \in [\underline{\theta}, \check{\theta})$, implying $\Delta(\check{\theta}) = 0$, $\Delta(\theta) > 0$ for $\theta \in [\underline{\theta}, \check{\theta})$ by Lemma A.6 and Proposition A.1.

Proof. We prove by contradiction, and split the proof into two parts.

Firstly, assume that γ is, though larger than unity, so small that (A.20) holds as a strict inequality. Then the proof is just the reversed proof of Proposition A.3. If there were any θ for which $\Delta'(\theta) > 0$, then $\Delta'(\bar{\theta}) > 0$ and $\Delta(\bar{\theta}) > 0$ would necessarily have to hold by Lemma A.5. By $\Delta(\bar{\theta}) > 0$, $\lambda(\bar{\theta}^-) = \lambda(\bar{\theta}) = 0$ in (A.15b). Substituting this in the $\Delta'(\theta) > 0$ condition (A.27) yields

$$0 > \lambda_0(\bar{\theta}) = \frac{\gamma-1}{\gamma} \bar{\theta} f(\theta), \quad (\text{A.41})$$

which contradicts $\gamma > 1$.

Secondly, assume that γ is so large that (A.20) does not hold. Then by Lemma A.3, $\mu(\theta) = 0 \forall \theta$. Suppose $\Delta(\bar{\theta}) > 0$, which would imply that there is no jump in $\lambda(\bar{\theta}^-)$; then from (A.15b),

$$\lambda(\theta) = \chi \cdot [F(\theta) - 1]. \quad (\text{A.42})$$

This implies $\lambda(\theta) < \lambda_0(\theta) = \frac{\gamma-1}{\gamma}\theta_0 f(\theta)$ (because $\gamma > 1$), which would imply $\Delta'(\theta) < 0$ by Lemma A.6. This would imply $\Delta(\theta) > 0$ globally, which is impossible by proposition A.1.

By contrast, suppose that $\Delta(\underline{\theta}) > 0$. Then, from (A.15a),

$$\lambda(\theta) = \chi \cdot F(\theta). \quad (\text{A.43})$$

Taking assumption A.1 into account, we have

$$\lambda(\theta) = \chi \cdot F(\theta) < \lambda_0(\theta) = \frac{\gamma-1}{\gamma}\theta f(\theta) \quad (\text{A.44})$$

$$\Leftrightarrow \left[\chi - \frac{\gamma-1}{\gamma} \right] \theta - \chi \underline{\theta} < 0. \quad (\text{A.45})$$

The first summand is negative by assumption, so the inequality holds.

□

To derive the tax path for $\gamma > 1$, we have to distinguish the two subcases used in the proof. The first subcase is $\chi - (\gamma - 1)/\gamma > 0$, which by Lemma A.3 allows a binding interval. Then we have just the reversed version of the $\gamma < 1$ case. For the interval $[\underline{\theta}, \check{\theta}]$,

$$\lambda(\theta) = \chi \cdot F(\theta) \quad (\text{A.46})$$

by (A.15a). For the interval $[\check{\theta}, \bar{\theta}]$, $\lambda(\theta) = \lambda_0(\theta)$ by Lemma A.2. Thus, $\lambda_0(\check{\theta}) =$

Case	τ	λ	μ	Δ
$\gamma < 1, \theta \leq \hat{\theta}$	$\gamma\theta (< \tau_{fb})$	$\lambda_0(\theta)$	> 0	0
$\gamma < 1, \theta > \hat{\theta}$	$\tau_{fb}(\theta) + \frac{F(\theta)-1}{f(\theta)} \frac{\gamma\chi}{1+\chi}$	$\chi [F(\theta) - 1]$	0	> 0
$\gamma = 1$	θ	0	$-$	0
$\gamma > 1, \chi - \frac{\gamma-1}{\gamma} > 0, \theta < \check{\theta}$	$\tau_{fb}(\theta) + \frac{F(\theta)}{f(\theta)} \frac{\gamma\chi}{1+\chi}$	$\chi F(\theta)$	0	> 0
$\gamma > 1, \chi - \frac{\gamma-1}{\gamma} > 0, \theta \geq \check{\theta}$	$\gamma\theta (> \tau_{fb})$	$\lambda_0(\theta)$	> 0	0
$\gamma > 1, \chi - \frac{\gamma-1}{\gamma} \leq 0$	$\tau_{fb}(\theta) + \frac{F(\theta)}{f(\theta)} \frac{\gamma\chi}{1+\chi}$	$\chi F(\theta)$	$-$	> 0 for $\theta < \bar{\theta}$

For $\hat{\theta}$, see (A.39), and for $\check{\theta}$, see (A.47). Where $\mu(\theta) > 0$ we have $\mu(\theta) = \left(\chi - \frac{\gamma-1}{\gamma}\right) f(\theta)$.

Table 1: The variables in the optimal contract.

$\chi \cdot F(\hat{\theta})$ separates the binding from the non-binding interval:

$$\check{\theta} = \frac{\chi}{\chi - \frac{\gamma-1}{\gamma}} \theta. \quad (\text{A.47})$$

If $\check{\theta} \geq \bar{\theta}$, there is no binding interval, and $\Delta'(\theta) < 0$ globally. Substituting $\lambda(\theta) = \chi F(\theta)$ (and Assumption A.1) in (A.9') and using Lemma A.2, the optimal tax schedule is

$$\tau^*(\theta) = \begin{cases} \frac{1+\gamma\chi}{1+\chi} \cdot \theta + \frac{\gamma\chi}{1+\chi} \cdot (\theta - \underline{\theta}) & \forall \theta \leq \check{\theta}, \\ \gamma\theta & \forall \theta \geq \check{\theta}. \end{cases} \quad (\text{A.48})$$

The second subcase is $\chi - (\gamma - 1)/\gamma \leq 0$. By Lemma A.3, there cannot be a binding interval in this case, so it must hold that $\Delta'(\theta) < 0$ for $\theta \in [\underline{\theta}, \bar{\theta})$, and $\Delta'(\bar{\theta}) \leq 0$. By Lemma A.6, $\Delta(\theta) > 0$ for $\theta \in [\underline{\theta}, \bar{\theta})$, and by Proposition A.1, $\Delta(\bar{\theta}) = 0$. (A.15a) then, again, implies

$$\lambda(\theta) = \chi \cdot F(\theta), \quad (\text{A.49})$$

so the tax is, again, defined by (A.48) with $\check{\theta} = \bar{\theta}$.

Table 1 summarizes all variants of the optimal contract, depending on the parameters.

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