Optimal Regulation of Private Production Contracts with Environmental Externalities

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Abstract

We address the problem of optimal regulation of an industry where the production of an environmentally polluting output is contracted with independent agents. The provision of production inputs is divided between the principal and the agent such that the production externality results from their joint actions. The main result shows that in a three-tier hierarchy (regulator-firm-agent) involving either a single-sided or a double-sided moral hazard problem, a principle of equivalence across regulatory schemes generally obtains. The only task for the regulatory agency is to determine the optimal total fiscal revenue in each state of nature because any sharing of the regulatory burden between the firm and the agent would result in the same solution. The equivalence principle is upset only when the effects of regulation on the endogenous organizational choices of the industry are explicitly taken into account.

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1 Introduction

A substantial increase in the number of environmental clean-up cases in the U.S. during the 1980's has been coupled by an increase in the entry rate of small judgment proof firms into hazardous sectors (Ringleb and Wiggins, 1990). This phenomenon has been explained by the behavior of firms, trying to minimize the liability exposure, segregated their risky activities in small corporations. Such segregation was valuable because claimants were restricted to the assets of the small corporation typically unable to pay the associated liability damages. This result exposed the inefficiency of the tort liability as a primary institutional form for dealing with large-scale, long-term environmental hazards.

As a response to the above empirically identified problem, subsequent literature has largely moved towards the investigation of optimal schemes for lender's liability in the case of judgment-proof firms (e.g., Pitchford, 1995; Boyer and Laffont, 1997; and Balkenborg, 2001). There has been noticeably less interest in addressing these problems in a standard regulation framework. As the above literature on vicarious liability, the papers examining environmental regulation focused only on cases where agents alone influence the level of pollution whereas the principal has little direct means for prevention or abatement. For example, Chambers and Quiggin (1996) modelled a non-point source pollution problem as a multi-task principal-agent problem where the agents are independent farmers producing corn and polluting the environment and the principal is the regulatory agency.

In this paper we address the problem of the optimal regulation of an industry in which environmentally polluting stages in the production chain are contracted with independent agents. A distinct feature of the contractual relationship that we are interested in is the fact that the provision of production inputs is divided between the principal and the agents so the resulting environmental pollution is the consequence of their joint actions. The particular sector that we have in mind is agriculture and especially the livestock production, although the results can applied to other industries where environmentally hazardous activities are contracted or franchised to independent agents.

We model a trilateral relationship between the Environmental Protection Agency (EPA), the contractor (firm) and a agent (producer) with the technology characterized by a joint production of output (live animal weight) and pollution (waste). We assume that output is observable and verifiable and hence contractible whereas pollution is observable but not verifiable and hence not contractible. From a theoretical point of view, this three-tier hierarchical model can be compared to the recent modelling of supervisory problem in a hierarchy (Faure-Grimaud, Laffont and Martimort, 2000, Faure-Grimaud and Martimort, 2001) where the principal (here the EPA) uses an intermediary agent (here the principal) to regulate a final agent (here the producer). In our regulatory model, the information structure is quite simple with either single sided moral hazard or double sided moral hazard, and the use of instruments such as taxation of both contracting parties (rather than only producers) can be interpreted as a way to improve the regulation of producers only.

We found that in this three-tier hierarchy involving either a single-sided or a double-sided moral hazard problem, the principle of equivalence across regulatory schemes mostly obtains. In both situations, regardless of the tax legal incidence, for a given amount of tax revenue, the regulator can obtain the same outcome. His only task is to determine the optimal total tax revenue in each state because any sharing of the tax burden between the principal and the agent would result in the same optimal solution. In this regard our results provide an important extension of an earlier work by Segerson and Tietenberg (1992) who studied the structure of penalties in a three-tier hierarchy under the assumption of risk neutrality for all parties and moral hazard on the agent's side and showed that the efficient outcome can be reached by imposing a penalty on either party.

However, when the effects of regulation on the endogenous organizational choices of the industry are explicitly taken into account, the equivalence principle breaks down and the design of the optimal regulatory scheme becomes more complicated. When the regulator wants to foster contracting as a dominant mode of organizing livestock production, the optimal taxation scheme prescribes the minimal and maximal shares that the agent and the principal have to pay. In a situation where the EPA needs to simultaneously regulate independent producers and principal-agent contract organizations without being able to discriminate, a uniquely determined optimal division of the aggregate tax burden between the principal and the agent is necessary.

The rest of the paper is organized as follows. The next section is devoted to stylized facts on contracting in animal agriculture. The basic model is developed in section 3. In section 4 we analyze the case of a single-sided moral hazard in the relationship between the processor and the agent and in section 5 the case of a double-sided moral hazard. Section 6 investigates the consequences of endogenous organizational choice for the equivalence principles obtained earlier. Concluding remarks are given in section 7.

2 Contracting in Animal Agriculture: Institutions and Technology

Contracting became an integral part of the production and marketing of selected livestock commodities such as broilers, turkeys and hogs. The potential impact of livestock production on environmental quality has become a major concern in areas with high density of concentrated animal feeding operations (CAFOs). It is increasingly common for environmental advocacy groups to argue that contracting is an important cause of adverse environmental quality effects in livestock production, largely because contracting increases the scale of livestock operations, simultaneously reducing opportunities for economics of scope in livestock utilization through reduced specialization.

Most of the livestock contracts are production contracts. A production contract is an agreement between a processing firm (also known as integrator) and a farmer (grower) that binds the farmer to specific production practices. Growers provide land, production facilities, utilities (electricity and water) and labor. Housing and waste handling units have to be constructed and equipped in strict compliance with the integrator's specifications. Growers are also fully responsible for compliance with federal, state and local environmental laws regarding disposal of dead animals and manure. An integrator company provides animals to be grown to processing weight, feed, medications and services of field men who supervise the adherence to the contract stipulations and provide production and management expertise. Typically, the company also owns and operates hatcheries, feed mills and processing plants, and provides transportation of feed and live animals. The integrator also decides on the volume of production both in terms of the rotations of batches on a given farm and the density of animals inside the house.

The most notable characteristic of modern livestock production systems based on contracts has been the shift to large-scale, intensive, specialized, confined animal operations. Opponents of such production systems cite many negative environmental impacts of increased geographic concentration of manure stocks. Among various externalities generated by the production and management of animal waste, nutrient runoff and leaching and air quality problems (ammonia emissions) are the most pervasive ones. For both of those, nutrient management plays a critical role. The nutrients of greatest concern are nitrogen and phosphorus. The amount of nutrients from animal waste that ends up deposited in the environment is directly related to the type of animals raised, the composition of animal feed, and the waste management technology that farmers use. Once feed composition and the waste handling and storing technology are fixed, the amount of pollution (nutrient content in manure) generated by a particular type of animal (e.g., a sow, a feeder pig, or a finished hog) is more or less deterministic.

The problems associated with the design and implementation of environmental regulation of CAFOs are different than those related to regulating traditional family farms. In the later case the standard economic prescription of taxing the externality such that the polluter pays the environmental cost of his action is not feasible due the non-point source nature of the pollution problem (see for example Innes, 2000). On the contrary, CAFOs are more similar to point source industrial polluters, hence some of the traditional regulatory instruments may prove to be adequate. However, the fact that a significant portion of CAFOs are in fact contract operations makes the design of the regulatory policy regimes substantially different. Actually, the incidence of the regulatory compliance cost is not obvious because it is likely to be subject to changes in contractual terms between growers and integrators.

An obvious solution to manure nutrient management problem is the source reduction. Pollution can be reduced by restricting the output or by reducing the amount of unusable nutrients in feed.[1] The former regulatory scheme is easily implementable because the output is readily observable by all interested parties. The later scheme is considerably more complicated because the precise feed composition is known only to the integrator and could be discovered by the growers and the regulator only after bearing the costs of laboratory analysis. The regulatory objective can be however achieved by providing the integrator with the incentives to use environmentally friendly feed instead of the traditional environmentally unfriendly mix, even when this type of feed is less productive (more costly) in terms of feed efficiency.

The importance of animal waste pollution as a cause of water quality problems has been recognized by the Clean Water Action Plan. Currently, the U.S. Environmental Protection Agency (EPA) is proposing to revise and update regulations that address the impacts of waste generated by CAFOs on water quality (EPA, 2001). This policy initiative motivates the research carried out in this paper. The main question we address is how to regulate an industry where production choices are affected by the signed contracts rather than by the independent producer optimizations.

[1] The amount of nitrogen in manure can be reduced by substituting synthetic amino-acids for crude proteins (corn, soybeans) in animal feed. The phosphorus pollution can be reduced by adding phytase to the diets. When the prices of corn and soybeans are high, it may be actually profitable to replace crude proteins with synthetic ones. On the other hand, rations based on phytase are always more expensive than the regular inorganic phosphorus diets (for details see Vukina, 2003).

3 The Basic Model

3.1 Assumptions and notation

We model an institutional structure with three players: the regulator (EPA), the principal (P) and the agent (A). This structure corresponds to the integrator firm contracting the production of live animals with independent producers (growers). The production of output generates a negative externality that needs to be regulated by the EPA.

The production process is described as follows. An agent exerts effort $e \in \{\underline{e}, \overline{e}\}$ that the principal cannot observe and the principal supplies the production input $x \in \{\underline{x}, \overline{x}\}$. The production input of concern in the case of livestock production is animal feed. The principal can choose either good feed $\underline{x}$ which is less efficient in the production of output (live weight) but environmentally friendlier or bad feed $\overline{x}$ which is highly productive but more polluting. Effort e and input x generate output $q \in \{\underline{q}, \overline{q}\}$ with $\underline{q} < \overline{q}$ and pollution $d = h(q) \in \{\underline{d}, \overline{d}\}$ with $\underline{d} \leq \overline{d}$.

The production technology depends on input x provided by P and effort e provided by A and is described by the following stochastic process

$$P(\overline{q} \mid e, x) = 1 - P(\underline{q} \mid e, x) = \theta(x)\pi(e)$$

with the following normalization $\theta(\overline{x}) = 1$, $\theta(\underline{x}) = \theta < 1$, and notation $\pi(\underline{e}) = \underline{\pi}$ and $\pi(\overline{e}) = \overline{\pi} > \underline{\pi}$. Pollution is a production externality that is jointly determined with the production state of nature. We call the high state of nature the case where production and pollution are high and the low state of nature the case where they are low.

The cost of effort for the agent is normalized to e, the level of effort. The input cost for the principal is $C(x)$ with the normalization $C(\overline{x}) = 0$ and $C(\underline{x}) = c > 0$.

We assume that production is observable and verifiable which implies that it is contractible. In addition we assume that pollution is also observable but not verifiable implying that neither the EPA nor the principal can write contracts contingent on pollution damages. However, the optimal regulatory scheme would be exactly the same if pollution were verifiable because it is simply a joint outcome of the production process.

The principal and the agent contract the production of output q. Because of the moral hazard problem, the wage w received by the agent needs to be contingent on production. The contract is then simply $\{w(\underline{q}) = \underline{w}, w(\overline{q}) = \overline{w}\}$. Before contracting between P and A occurs, the EPA commits to some regulatory scheme to control pollution. Given the pollution level, P and A are required to pay a fee to the EPA in the amount of $F(q) \in \{F(\underline{q}) = \underline{F}, F(\overline{q}) = \overline{F}\}$ and $T(q) \in \{T(\underline{q}) = \underline{T}, T(\overline{q}) = \overline{T}\}$. Total tax revenue is then $R(q) = F(q) + T(q) \in \{R(\underline{q}) = \underline{R}, R(\overline{q}) = \overline{R}\}$. The objective of the EPA is to maximize the expected difference between the tax revenue and the environmental damage, $\mathbb{E}(R - d)$.[2]

The agent's utility function is separable in consumption and effort and equal to $U(w - T) - e$ where U is increasing concave and e is the cost of effort. The principal's utility function is $V(q - F - w - C(x))$ where V is also increasing concave. Both P and A are risk averse. The exogenous reservation utilities of the principal and the agent are respectively U_0 and V_0. Throughout the paper, we will sometimes consider a special case where P and A have constant absolute risk aversion utility functions of the form $U(Y) = -\frac{1}{\sigma_U}\exp(-\sigma_U Y)$ and $V(Y) = -\frac{1}{\sigma_V}\exp(-\sigma_V Y)$.

3.2 First-Best

The first-best outcome obtains in case where there is no asymmetry of information among the players, that is, both agent's effort and principal's input are observable by everybody. Assuming that it is socially optimal to always produce with low effort $\underline{e}$ and environmentally friendly feed $\underline{x}$, the regulatory agency can simply mandate the use of these inputs. In a standard procedure, the problem can be solved in two steps. First, solve the principal-agent optimal contracting problem given some regulatory scheme $\{\underline{F}, \overline{F}, \underline{T}, \overline{T}\}$ and then solve the EPA's problem taking into account the endogenous optimal contract from the first step. It is easy to see that perfect risk sharing between the principal and the agent is then achieved

[2] This objective is quite general and can take into account any net social surplus obtained in each state of nature simply by redefining the value of d.

meaning that the payment to the agent $\overline{w}_0(\overline{F},\overline{T})$ and $\underline{w}_0(\underline{F},\underline{T})$ must solve the following equation

$$\frac{V'(\overline{q}-\overline{F}-\overline{w}_0(\overline{F},\overline{T})-c1_{x=\underline{x}})}{V'(\underline{q}-\underline{F}-\underline{w}_0(\underline{F},\underline{T})-c1_{x=\underline{x}})}=\frac{U'(\overline{w}_0(\overline{F},\overline{T})-\overline{T})}{U'(\underline{w}_0(\underline{F},\underline{T})-\underline{T})}.$$

Next, we study two cases, one in which input x is observable by everybody and the other where x is private information of the principal and hence unobservable by the EPA and the agent. In the first case there is a single moral hazard problem associated with the agent's effort, whereas in the second case there is a double moral hazard problem associated with the agent's effort and the principal's input.

4 Optimal Regulation under Single Moral Hazard

Absent any regulation, the principal would always selects the more polluting input $\overline{x}$ that results in the environmental damage $\overline{d}$. The regulatory intervention can be justified on the ground that some optimal scheme can implement the less polluting input $\underline{x}$ resulting in $\underline{d}$ at a cost lower than the expected benefit from damage reduction.[3] We start by assuming that x is observable by the EPA and therefore the principal is required to supply $\underline{x}$. The other case will be studied in section 5.

With respect to effort e, there are two possible cases. In the first case, the regulator wants to implement low effort $\underline{e}$ which is in conflict with the principal's preference under no regulation scenario. In the second case, the EPA wants to implement $\overline{e}$, which is the same effort level that P would implement absent any regulation, hence there is no conflict of interest. The latter is of course the case if the damage is the same in each state and, by a continuity argument, when the gap between damages $\overline{d}$ and $\underline{d}$ is sufficiently low. Then, the EPA's problem is only to extract the principal's rent knowing his reservation utility V_0. The results of the no conflict of interest case are less interesting and relegated to Appendix A.

[3]The remaining case where using the bad input $\overline{x}$ is better for society is less interesting and will be ignored, although it can be solved in the same fashion as other problems in this paper.

We solve the problem in two steps. First, we solve the optimal contracting problem between P and A given some regulatory scheme $\{\underline{F}, \overline{F}, \underline{T}, \overline{T}\}$. Then, we solve the EPA's problem taking into account the endogenous optimal contract.

4.1 The optimal contract between P and A

With incentives to implement low effort $\underline{e}$ and the mandate from the EPA to use the good input $\underline{x}$, the principal's program is

$$\begin{array}{ll} \max_{\underline{w},\overline{w}} \theta\underline{\pi}V(\overline{q}-\overline{F}-\overline{w}-c)+(1-\theta\underline{\pi})V(\underline{q}-\underline{F}-\underline{w}-c) & \\ s.t.\ \theta\underline{\pi}U(\overline{w}-\overline{T})+(1-\theta\underline{\pi})U(\underline{w}-\underline{T})-\underline{e}\geq U_0 & (\mu) \\ \theta\underline{\pi}U(\overline{w}-\overline{T})+(1-\theta\underline{\pi})U(\underline{w}-\underline{T})-\underline{e}\geq \theta\overline{\pi}U(\overline{w}-\overline{T})+(1-\theta\overline{\pi})U(\underline{w}-\underline{T})-\overline{e} & (\lambda) \end{array} \tag{1}$$

where μ and λ are Lagrange multipliers associated with the participation and incentive constraints. To avoid notational clutter, let $V(\overline{q}-\overline{F}-\overline{w}-c)=\overline{V}$, $V(\underline{q}-\underline{F}-\underline{w}-c)=\underline{V}$, $U(\overline{w}-\overline{T})=\overline{U}$, $U(\underline{w}-\underline{T})=\underline{U}$, and $V'(\overline{q}-\overline{F}-\overline{w}-c)=\overline{V}'$, $V'(\underline{q}-\underline{F}-\underline{w}-c)=\underline{V}'$, $U'(\overline{w}-\overline{T})=\overline{U}'$, $U'(\underline{w}-\underline{T})=\underline{U}'$. The program is concave, so that first order conditions are sufficient and give

$$\lambda = \frac{(1-\theta\underline{\pi})\underline{\pi}}{\underline{\pi}-\overline{\pi}}\frac{\overline{V}'\underline{U}'-\underline{V}'\overline{U}'}{\underline{U}'\overline{U}'} \tag{2}$$

$$\mu = \frac{\theta\underline{\pi}\overline{V}'\underline{U}'+(1-\theta\underline{\pi})\underline{V}'\overline{U}'}{\underline{U}'\overline{U}'} > 0 \tag{3}$$

because U and V are increasing.

The participation constraint is thus binding ($\mu > 0$), that is $\theta\underline{\pi}(\overline{U}-\underline{U})+\underline{U}=U_0+\underline{e}$. If, in addition, the incentive constraint is also binding, i.e. if $\lambda > 0$ (which is the case provided that $\overline{e}$ is not too large),[4] we obtain the following results

$$\begin{aligned} \underline{U} &= U_0 + \frac{\overline{\pi}\underline{e}-\underline{\pi}\overline{e}}{\overline{\pi}-\underline{\pi}} \\ \overline{U} &= \underline{U} + \frac{\overline{e}-\underline{e}}{\theta(\overline{\pi}-\underline{\pi})} > \underline{U} \end{aligned}$$

since $\underline{e} < \overline{e}$ and $\overline{\pi} > \underline{\pi}$. Because the incentive constraint is binding, the net utility of the agent in the low state is lower than that in the high state (in the opposite case, $\overline{U} < \underline{U}$, the

[4] Alternatively, the incentive constraint could be non-binding (for example, when $\overline{e}$ tends to $+\infty$), in which case the incentive problem would disappear and the first-best would be achieved.

incentive constraint would be trivially strictly satisfied). Notice that $\underline{U}$ does not depend on θ whereas $\overline{U}$ is decreasing in θ indicating that the more the good input reduces the expected production, the less powerful will be the incentives given to the agent. Moreover, looking at the way the contract depends on the taxes proposed by the EPA, we get the following proposition:

Proposition 1 *The optimal wages $\overline{w}^*$ and $\underline{w}^*$ are such that $\overline{w}^*$ depends only on $(\overline{F}, \overline{T})$, $\underline{w}^*$ depends only on $(\underline{F}, \underline{T})$ and*

$$\frac{\partial \overline{w}^*}{\partial \overline{T}} = 1 + \frac{\partial \overline{w}^*}{\partial \overline{F}} = \frac{\overline{\sigma}_U}{\overline{\sigma}_U + \overline{\sigma}_V} \in (0,1) \tag{4}$$

$$\frac{\partial \underline{w}^*}{\partial \underline{T}} = 1 + \frac{\partial \underline{w}^*}{\partial \underline{F}} = \frac{\underline{\sigma}_U}{\underline{\sigma}_U + \underline{\sigma}_V} \in (0,1) \tag{5}$$

where $\overline{\sigma}_U = -\frac{\overline{U}''}{\overline{U}'}$, $\overline{\sigma}_V = -\frac{\overline{V}''}{\overline{V}'}$, $\underline{\sigma}_U = -\frac{\underline{U}''}{\underline{U}'}$, $\underline{\sigma}_V = -\frac{\underline{V}''}{\underline{V}'}$ are the rates of absolute risk aversion of P and A at consumption levels in good or bad states.
Agent's net wages ($\overline{w}^* - \overline{T}$ and $\underline{w}^* - \underline{T}$) depend only on the total tax revenue R, that is

$$\frac{\partial(\overline{w}^* - \overline{T})}{\partial \overline{R}} = \frac{\partial(\overline{w}^* - \overline{T})}{\partial \overline{T}} = \frac{\partial(\overline{w}^* - \overline{T})}{\partial \overline{F}} = \frac{-\overline{\sigma}_V}{\overline{\sigma}_U + \overline{\sigma}_V} \in (-1,0)$$

$$\frac{\partial(\underline{w}^* - \underline{T})}{\partial \underline{R}} = \frac{\partial(\underline{w}^* - \underline{T})}{\partial \underline{T}} = \frac{\partial(\underline{w}^* - \underline{T})}{\partial \underline{F}} = \frac{-\underline{\sigma}_V}{\underline{\sigma}_U + \underline{\sigma}_V} \in (-1,0)$$

Similarly, the principal's profits ($\overline{q} - \overline{F} - \overline{w}^* - c$ and $\underline{q} - \underline{F} - \underline{w}^* - c$) depend only on the total tax revenue R

$$\frac{\partial(\overline{w}^* + \overline{F})}{\partial \overline{R}} = \frac{\partial(\overline{w}^* + \overline{F})}{\partial \overline{T}} = \frac{\partial(\overline{w}^* + \overline{F})}{\partial \overline{F}} = \frac{\overline{\sigma}_V}{\overline{\sigma}_U + \overline{\sigma}_V} \in (0,1)$$

$$\frac{\partial(\underline{w}^* + \underline{F})}{\partial \underline{R}} = \frac{\partial(\underline{w}^* + \underline{F})}{\partial \underline{T}} = \frac{\partial(\underline{w}^* + \underline{F})}{\partial \underline{F}} = \frac{\underline{\sigma}_V}{\underline{\sigma}_U + \underline{\sigma}_V} \in (0,1)$$

Proof. See Appendix C. ■

Proposition 1 provides a set of important results. First, wages in each state depend only on taxes corresponding to the same state. Second, an increase in taxes T on A increases the wage but the agent is not fully compensated. Therefore, when taxes increase, net wages decrease. Similarly, a reduction in taxes decreases wages but the wage reduction is less than the tax reduction. Third, the changes in wages with respect to taxes T depend on the ratio of the absolute risk aversions of the agent and the principal. The more risk averse A relative to P, the less net wages respond to taxes on A, that is the more insurance will the principal provide to agent's net wage against changing taxes. In other words, the principal absorbs the larger part of the net wage change coming from the changes in taxes when the agent is more risk averse. Fourth, wages also depend on taxes F paid by the principal. Finally, the agent's net wage $w - T$ changes exactly in the same way with respect to taxes T or F. Actually, wages respond to the change in taxes in such a way that an increase in taxes $\overline{T}$ can be compensated exactly by a decrease in $\overline{F}$ to leave net wages $\overline{w}^*(\overline{F}, \overline{T}) - \overline{T}$ unchanged. The same is true for the other state of nature. This result follows from $\frac{\partial \overline{w}^*}{\partial \overline{T}} - \frac{\partial \overline{w}^*}{\partial \overline{F}} = \frac{\partial \underline{w}^*}{\partial \underline{T}} - \frac{\partial \underline{w}^*}{\partial \underline{F}} = 1$.

With the incentive constraint binding, i.e. $\lambda > 0$, one can show the following inequality[5]

$$\frac{\overline{V}'}{\underline{V}'} < \frac{\overline{U}'}{\underline{U}'} \tag{6}$$

Setting $\overline{w}_0(\overline{F}, \overline{T})$ and $\underline{w}_0(\underline{F}, \underline{T})$ equal the wages that would accomplish the perfect risk sharing between P and A for a given regulatory scheme, the inequality (6) shows that wages $\overline{w}^*(\overline{F}, \overline{T})$ and $\underline{w}^*(\underline{F}, \underline{T})$ are such that $\overline{w}^*(\overline{F}, \overline{T}) < \overline{w}_0(\overline{F}, \overline{T})$ or $\underline{w}^*(\underline{F}, \underline{T}) > \underline{w}_0(\underline{F}, \underline{T})$.

With CARA utility functions for P and A, (6) implies that $\overline{w}^*(\overline{F}, \overline{T}) - \underline{w}^*(\underline{F}, \underline{T}) < \overline{w}_0(\overline{F}, \overline{T}) - \underline{w}_0(\underline{F}, \underline{T})$. Therefore, the gap between wages in good and bad states is reduced compared to the case with the perfect risk sharing. Given the fact that the risk aversion coefficients are constant, we obtain

$$\frac{\partial \overline{w}^*}{\partial \overline{T}} = \frac{\partial \underline{w}^*}{\partial \underline{T}} = 1 + \frac{\partial \overline{w}^*}{\partial \overline{F}} = 1 + \frac{\partial \underline{w}^*}{\partial \underline{F}} = \frac{\sigma_U}{\sigma_U + \sigma_V} \in (0, 1)$$

and the optimal wage contracts are linear with respect to taxes, that is $\overline{w}^*(\overline{F}, \overline{T}) = \frac{\sigma_U}{\sigma_U + \sigma_V} \overline{T} - \frac{\sigma_V}{\sigma_U + \sigma_V} \overline{F} + \overline{w}^*(0, 0)$ and $\underline{w}^*(\underline{F}, \underline{T}) = \frac{\sigma_U}{\sigma_U + \sigma_V} \underline{T} - \frac{\sigma_V}{\sigma_U + \sigma_V} \underline{F} + \underline{w}^*(0, 0)$. In this case, $\overline{w}^*(0, 0)$ and

[5] Notice that the reverse inequality in (6) is obtained when the principal wants to implement $\overline{e}$. For example, this will happen if there is no regulation.

$\underline{w}^*(0,0)$ are the optimal wages with both taxes set to zero obtained as

$$\underline{w}^*(0,0) = U^{-1}(U_0 + \frac{\overline{\pi}\underline{e} - \underline{\pi}\overline{e}}{\overline{\pi} - \underline{\pi}})$$
$$\overline{w}^*(0,0) = U^{-1}(\underline{U} + \frac{\overline{e} - \underline{e}}{\theta(\overline{\pi} - \underline{\pi})}).$$

4.2 The Regulator's problem

Given the optimal contract between the principal and the agent, the EPA's program is to choose taxes F and T to maximize the expected tax revenue net of environmental damage $\mathbb{E}(R-d)$, with $R = F + T$, subject to the participation constraint of the principal:

$$\max_{\underline{F},\overline{F},\underline{T},\overline{T}} \theta\underline{\pi}(\overline{F} + \overline{T} - \overline{d}) + (1-\theta\underline{\pi})(\underline{F} + \underline{T} - \underline{d}) \quad s.t.\ \theta\underline{\pi}\overline{V}^* + (1-\theta\underline{\pi})\underline{V}^* \geq V_0 \qquad (\eta) \tag{7}$$

where $\overline{V}^* = V(\overline{q} - \overline{F} - \overline{w}^*(\overline{F},\overline{T}) - c)$, $\underline{V}^* = V(\underline{q} - \underline{F} - \underline{w}^*(\underline{F},\underline{T}) - c)$ and $\overline{w}^*(\overline{F},\overline{T})$ and $\underline{w}^*(\underline{F},\underline{T})$ are the solutions to (1).

The program being concave, the first order conditions are sufficient

$$\theta\underline{\pi} = \eta\{\theta\underline{\pi}(1 + \frac{\partial\overline{w}^*}{\partial\overline{F}})\overline{V}^{*\prime} + (1-\theta\underline{\pi})\frac{\partial\underline{w}^*}{\partial\overline{F}}\underline{V}^{*\prime}\} \tag{8}$$
$$1-\theta\underline{\pi} = \eta\{\theta\underline{\pi}\frac{\partial\overline{w}^*}{\partial\underline{F}}\overline{V}^{*\prime} + (1-\theta\underline{\pi})(1 + \frac{\partial\underline{w}^*}{\partial\underline{F}})\underline{V}^{*\prime}\} \tag{9}$$
$$\theta\underline{\pi} = \eta\{\theta\underline{\pi}\frac{\partial\overline{w}^*}{\partial\overline{T}}\overline{V}^{*\prime} + (1-\theta\underline{\pi})\frac{\partial\underline{w}^*}{\partial\overline{T}}\underline{V}^{*\prime}\} \tag{10}$$
$$1-\theta\underline{\pi} = \eta\{\theta\underline{\pi}\frac{\partial\overline{w}^*}{\partial\underline{T}}\overline{V}^{*\prime} + (1-\theta\underline{\pi})\frac{\partial\underline{w}^*}{\partial\underline{T}}\underline{V}^{*\prime}\} \tag{11}$$

Substituting conditions (4) and (5) from Proposition 1 into (8)-(11) we get

$$\eta = \frac{1}{(1 + \frac{\partial\overline{w}^*}{\partial\overline{F}})\overline{V}^{*\prime}} = \frac{\overline{\sigma}_U + \overline{\sigma}_V}{\overline{\sigma}_U}\frac{1}{\overline{V}^{*\prime}} > 0 \tag{12}$$
$$\frac{\overline{V}^{*\prime}}{\underline{V}^{*\prime}} = \frac{\frac{\partial\underline{w}^*}{\partial\overline{T}}}{\frac{\partial\overline{w}^*}{\partial\overline{T}}} = \frac{\underline{\sigma}_U}{\overline{\sigma}_U}\frac{\overline{\sigma}_U + \overline{\sigma}_V}{\underline{\sigma}_U + \underline{\sigma}_V} \tag{13}$$

indicating that the principal's participation constraint (7) is binding because $\eta > 0$.

Condition (13) enables us to derive several important results. First, in equilibrium the principal's ex post utility levels are insensitive to the choice of regulatory instruments selected by the EPA that is

$$\frac{d\overline{V}^*}{d\overline{T}} = \frac{d\underline{V}^*}{d\underline{T}} = \frac{d\overline{V}^*}{d\overline{F}} = \frac{d\underline{V}^*}{d\underline{F}} = \frac{d\overline{V}^*}{d\overline{R}} = \frac{d\underline{V}^*}{d\underline{R}}$$

Second, (13) also implies that

$$\begin{aligned}\frac{d\mathbb{E}V^*}{d\overline{T}} &= \frac{d\mathbb{E}V^*}{d\overline{F}} = \frac{d\mathbb{E}V^*}{d\overline{R}} \\ \frac{d\mathbb{E}V^*}{d\underline{T}} &= \frac{d\mathbb{E}V^*}{d\underline{F}} = \frac{d\mathbb{E}V^*}{d\underline{R}}\end{aligned}$$

meaning that as far as the principal's expected utility is concerned, the choice of tax instruments in both states of nature is irrelevant. From the perspective of the principal, taxing either P or A contingently on the state of nature is equivalent. Finally, the ratio of marginal utilities of the principal in high and low states depends on the ratio of absolute risk aversions of the agent and the principal in high and low states.

If the principal's utility function V exhibits increasing absolute risk aversion which includes in particular the CARA (Constant Absolute Risk Aversion) case, regardless of utility function U, we have $\frac{\overline{V}^{*\prime}}{\underline{V}^{*\prime}} \geq 1$ ($= 1$ if CARA). Actually, if $\frac{\overline{V}^{*\prime}}{\underline{V}^{*\prime}} < 1$, then with increasing absolute risk aversion $\overline{\sigma}_V \geq \underline{\sigma}_V$ implying that $\frac{\overline{\sigma}_U+\overline{\sigma}_V}{\underline{\sigma}_U+\underline{\sigma}_V} \geq \frac{\overline{\sigma}_U+\underline{\sigma}_V}{\underline{\sigma}_U+\underline{\sigma}_V} > \frac{\overline{\sigma}_U}{\underline{\sigma}_U}$, because $\frac{y+a}{x+a} > \frac{y}{x}$ $\forall x,\ y,\ a > 0$ which would imply $\frac{\overline{V}^{*\prime}}{\underline{V}^{*\prime}} > 1$. Moreover, because of the conflict of interest between EPA and P about effort, we have $\frac{\overline{V}^{*\prime}}{\underline{V}^{*\prime}} < \frac{\overline{U}^{*\prime}}{\underline{U}^{*\prime}}$. Thus $1 < \frac{\overline{V}^{*\prime}}{\underline{V}^{*\prime}} < \frac{\overline{U}^{*\prime}}{\underline{U}^{*\prime}}$ implies that $\overline{q} - \overline{F}^* - \overline{w}^*(\overline{F}^*, \overline{T}^*) - c < \underline{q} - \underline{F}^* - \underline{w}^*(\underline{F}^*, \underline{T}^*) - c$ and $\overline{w}^*(\overline{F}^*, \overline{T}^*) - \overline{T}^* < \underline{w}^*(\underline{F}^*, \underline{T}^*) - \underline{T}^*$ which implies $\overline{F}^* + \overline{w}^*(\overline{F}^*, \overline{T}^*) - \underline{F}^* - \underline{w}^*(\underline{F}^*, \underline{T}^*) > \overline{q} - \underline{q} > 0$ and therefore $\overline{R}^* = \overline{F}^* + \overline{T}^* > \underline{R}^* = \underline{F}^* + \underline{T}^*$. This implies that total taxes in the high state (higher production and higher pollution) are greater than that in the low state.

Using Proposition 1, we can show the following

Proposition 2 ***(Equivalence Principle - I)*** *Given some total tax revenue $(\overline{R}^*, \underline{R}^*)$ that the EPA wants to raise, taxing P or A or both is equivalent. Any taxation scheme satisfying $\overline{T} + \overline{F} = \overline{R}^*$ and $\underline{T} + \underline{F} = \underline{R}^*$ results in the same outcome and generates the same utility levels to all parties. EPA's regulation only determines the optimal total tax revenue in each* *state and any sharing of total optimal taxes between P and A results in the same optimal solution.*

Proof. See Appendix D. ■

This equivalence principle implies, for instance, that the optimal taxation scheme $(\overline{R}^*, \underline{R}^*)$ can be implemented by taxing only P ($\overline{F}^* = \overline{R}^*$, $\underline{F}^* = \underline{R}^*$), or A ($\overline{T}^* = \overline{R}^*$, $\underline{T}^* = \underline{R}^*$). Also, the EPA could subsidize A and tax P (for example, $\overline{T}^* = -S$, $\underline{T}^* = -S$, $\overline{F}^* = \overline{R}^* + S$, $\underline{F}^* = \underline{R}^* + S$). Consequently, only total tax revenue matters. When the total tax burden increases, it is shared between P and A according to their relative risk aversion (see Proposition 1). It is to be noted that this equivalence principle is quite strong and robust. In particular, it can be straightforwardly extended to a version of the model with many or continuous states of nature and more or continuous levels of effort.

Of course, if EPA values the tax revenue collected from the principal and the agent differently (for example because of different administrative costs) then the equivalence principle would disappear and designing the optimal regulatory scheme would require placing the full tax burden on the party for which tax collection is the least costly. The equivalence principle is also derived under the assumption that the principal and the agent agreed upon an optimal contract after the regulatory scheme was announced by the EPA. Any rigidity or impediment in the implementation of this optimal contract would break the equivalence principle.

In the CARA case, (13) implies that $V^{*\prime}(\overline{q} - \overline{F} - \overline{w}^*(\overline{F}, \overline{T}) - c) = V^{*\prime}(\underline{q} - \underline{F} - \underline{w}^*(\underline{F}, \underline{T}) - c)$ that is

$$\begin{aligned}
\overline{q} - \underline{q} &= (\overline{F} - \underline{F}) + (\overline{w}^*(\overline{F}, \overline{T}) - \underline{w}^*(\underline{F}, \underline{T})) \\
\overline{q} - \underline{q} &= \frac{\sigma_U}{\sigma_U + \sigma_V}[(\overline{F} + \overline{T}) - (\underline{F} + \underline{T})] + \overline{w}^*(0,0) - \underline{w}^*(0,0)
\end{aligned}$$

Moreover, (6) implies $\frac{\underline{U}'}{\overline{U}'} > 1$, that is, $\exp -\sigma_U[\overline{w}^*(\overline{F}, \overline{T}) - \underline{w}^*(\underline{F}, \underline{T}) - (\overline{T} - \underline{T})] > 1$ implying $\overline{w}^*(\overline{F}, \overline{T}) - \overline{T} < \underline{w}^*(\underline{F}, \underline{T}) - \underline{T}$. Therefore, net wage is lower in the high state case than in the low state case.

At this point, it is worth studying the case where the principal is risk neutral. It is frequently (but not always) the case that the principal offering production contracts to independent farmers is a large publicly traded company. Public companies are known to spread risk among their shareholders, so the assumption of risk neutrality is plausible in many situations. To carry out the analysis for the risk neutral case, we can simply set $V' \equiv 1$ (and $V'' \equiv 0$) which implies that

$$\begin{aligned} \frac{\partial \overline{w}^*}{\partial \overline{F}} &= \frac{\partial \underline{w}^*}{\partial \underline{F}} = 0 \\ \frac{\partial \overline{w}^*}{\partial \overline{T}} &= \frac{\partial \underline{w}^*}{\partial \underline{T}} = 1. \end{aligned}$$

These results show that the wages do not depend on taxes F that the principal pays but rather only on taxes that the agent pays T. Agent's net wages are constant with respect to all taxes. In contrast to the risk averse principal case where total taxes affect net wages, the EPA's taxation policy has no bearing on A's behavior and on his wage. The principal insures agent's revenue from any tax change although A's payment varies across states of nature.

5 Optimal Regulation under Double Sided Moral Hazard

So far in the paper, we have assumed that x was observable by all parties and it was easy for the EPA to mandate the use of good input. However, if x is unobservable, mandating the use of environmentally friendly input $\underline{x}$ is not possible, the principal will always choose bad input $\overline{x}$. If the regulatory agency wants to stimulate the use of good input it has to design a scheme such that the principal will voluntarily choose the good input.[6]

As before, in the main text we are going to analyze the case with conflict of interest on effort, while the case with no conflict of interest on effort is referred to in Appendix B.

[6] Of course, it will not always make sense for the EPA to give incentives to the principal to choose the good input because this can be too costly compared to the environmental benefits. Here we assume that it is always valuable to the EPA to elicit the use of environmentally friendly input.

When there is a conflict of interest between P and EPA on both effort e and input x, the EPA chooses taxes to induce the principal to implement $\underline{e}$ and $\underline{x}$. The principal's program ends up being the same as in (1) where x was observable. Therefore, Proposition 1 still holds. However with unobservable x, the EPA's problem is augmented by an additional incentive constraint that guarantees the correct response of the principal regarding the utilization of good input

$$\begin{array}{ll} \max\limits_{\underline{F},\overline{F},\underline{T},\overline{T}} \theta\underline{\pi}(\overline{F}+\overline{T}-\overline{d})+(1-\theta\underline{\pi})(\underline{F}+\underline{T}-\underline{d}) & \\ s.t.\ \theta\underline{\pi}\overline{V}^{**}+(1-\theta\underline{\pi})\underline{V}^{**}\geq V_0 & (\eta) \\ \theta\underline{\pi}\overline{V}^{**}+(1-\theta\underline{\pi})\underline{V}^{**}\geq \underline{\pi}\overline{V}^{*}+(1-\underline{\pi})\underline{V}^{*} & (\gamma) \end{array} \tag{14}$$

For notational convenience, we use ** to indicate solutions when x is not observable whereas we keep * to label solutions of Section 4 where x is observable. Following this convention, $\overline{V}^{**}=V(\overline{q}-\overline{F}-\overline{w}^{**}-c)$, $\underline{V}^{**}=V(\underline{q}-\underline{F}-\underline{w}^{**}-c)$, where $\overline{w}^{**}$ and $\underline{w}^{**}$ are the solutions to (1) and $\overline{V}^{*}=V(\overline{q}-\overline{F}-\overline{w}^{*})$, $\underline{V}^{*}=V(\underline{q}-\underline{F}-\underline{w}^{*})$ and wages $\overline{w}^{*}$ and $\underline{w}^{*}$ are the solutions to the principal's problem when he is not required to use the good input. These are the same wage functions as in Proposition 1 with $c=0$ and $\theta=1$.

Using Proposition 1, we can extend the equivalence principle to the unobservable input case:

Corollary 3 ***(Equivalence Principle - II)*** *Given some total tax revenue $\overline{R}^{**}$, $\underline{R}^{**}$ that the EPA wants to raise, taxing P or A or both is equivalent, that is, any taxation scheme satisfying $\overline{T}+\overline{F}=\overline{R}^{**}$ and $\underline{T}+\underline{F}=\underline{R}^{**}$ results in the same outcome and generates the same utility levels to all parties. The EPA's regulation only determines the optimal total tax revenue in each state and any sharing of total optimal taxes between P and A results in the same optimal solution.*

Proof. See Appendix E. ■

However, in spite of the validity of the equivalence principle in the unobservable input case, the optimal regulation will change. Using the first order conditions of the problem stated above and the results of Proposition 1, we state the following proposition:

Proposition 4 *The ratio of marginal effects of taxes on the principal's utility in high and low states satisfies*

$$\frac{\frac{d\overline{V}^{**}}{d\overline{T}}}{\frac{d\underline{V}^{**}}{d\underline{T}}} = \frac{\frac{d\overline{V}^{**}}{d\overline{F}}}{\frac{d\underline{V}^{**}}{d\underline{F}}} = \left(\frac{\theta(1-\underline{\pi})}{1-\theta\underline{\pi}} + \frac{\theta(1-\theta)}{(1-\theta\underline{\pi})(\theta + \gamma \overline{V}^{*\prime} \frac{\partial \overline{w}^{*}}{\partial \overline{T}})} \right)^{-1} \tag{15}$$

$$1 \leq \frac{\frac{d\overline{V}^{**}}{d\overline{T}}}{\frac{d\underline{V}^{**}}{d\underline{T}}} = \frac{\frac{\partial \overline{w}^{**}}{\partial \overline{T}} \overline{V}^{**\prime}}{\frac{\partial \underline{w}^{**}}{\partial \underline{T}} \underline{V}^{**\prime}} < \frac{1-\theta\underline{\pi}}{\theta(1-\underline{\pi})}$$

and the ratio of marginal utilities satisfies

$$\frac{\underline{\sigma}_U^{**}}{\overline{\sigma}_U^{**}} \frac{\overline{\sigma}_U^{**} + \overline{\sigma}_V^{**}}{\underline{\sigma}_U^{**} + \underline{\sigma}_V^{**}} \leq \frac{\overline{V}^{**\prime}}{\underline{V}^{**\prime}} < \frac{1-\theta\underline{\pi}}{\theta(1-\underline{\pi})} \frac{\underline{\sigma}_U^{**}}{\overline{\sigma}_U^{**}} \frac{\overline{\sigma}_U^{**} + \overline{\sigma}_V^{**}}{\underline{\sigma}_U^{**} + \underline{\sigma}_V^{**}}$$

Proof. See Appendix F. ■

Proposition 4 indicates that the ratio of marginal effects of taxes on P's utility in high and low states is bounded below by 1 and bounded above by $\frac{1-\theta\underline{\pi}}{\theta(1-\underline{\pi})} = \frac{P(\overline{q}|\underline{e},\underline{x})}{P(\underline{q}|\underline{e},\underline{x})} \frac{P(\underline{q}|\underline{e},\overline{x})}{P(\overline{q}|\underline{e},\overline{x})} > 1$. Compared to the case where x was observable, the additional incentive constraint introduces a distortion in the optimal taxation. Note that if $\gamma = 0$ (incentive constraint not binding) or $\theta = 1$ (no difference between inputs $\overline{x}$ and $\underline{x}$ in the production process) in (15), then we obtain the same ratio as in the observable input case

$$\frac{\overline{V}^{**\prime}}{\underline{V}^{**\prime}} = \frac{\frac{\partial \underline{w}^{**}}{\partial \underline{T}}}{\frac{\partial \overline{w}^{**}}{\partial \overline{T}}}$$

and the distortion disappears.

Notice also that the result about the inequality of total tax revenue in the two states of nature ($\overline{R}^{*} > \underline{R}^{*}$) with non-decreasing absolute risk aversion of the principal and conflict of interest on effort still holds because $\frac{\underline{\sigma}_U^{**}}{\overline{\sigma}_U^{**}} \frac{\overline{\sigma}_U^{**}+\overline{\sigma}_V^{**}}{\underline{\sigma}_U^{**}+\underline{\sigma}_V^{**}} < \frac{\overline{V}^{**\prime}}{\underline{V}^{**\prime}}$ and $\frac{\overline{U}^{**\prime}}{\underline{U}^{**\prime}} > \frac{\overline{V}^{**\prime}}{\underline{V}^{**\prime}}$. In the CARA case, equation (15) implies $\frac{\overline{V}^{**\prime}}{\underline{V}^{**\prime}} = \exp\text{-}\sigma_V(\overline{q} - \underline{q} - (\overline{w}^{**} - \underline{w}^{**}) - (\overline{F}^{**} - \underline{F}^{**})) > 1 = \frac{\overline{V}^{*\prime}}{\underline{V}^{*\prime}} = \exp\text{-}\sigma_V(\overline{q} - \underline{q} - (\overline{w}^{*} - \underline{w}^{*}) - (\overline{F}^{*} - \underline{F}^{*}))$, that is, $\overline{q} - (\overline{w}^{**} + \overline{F}^{**}) - (\underline{q} - (\underline{w}^{**} + \underline{F}^{**})) < \overline{q} - (\overline{w}^{*} + \overline{F}^{*}) - (\underline{q} - (\underline{w}^{*} + \underline{F}^{*})) = 0$, indicating that the utility of P in high state is lower than in bad state ($\overline{V}^{**} < \underline{V}^{**}$) whereas they are equal when x is observable ($\overline{V}^{*} = \underline{V}^{*}$). The difference in net utility of P between low and high state is increased in absolute value compared to the case where x is observable. It means that in case where x is not observable by the EPA, the incentives to induce the implementation of the low effort are more powerful.

If the principal is risk neutral, then $\eta = 1$ and $\gamma = 0$, meaning that the principal's participation constraint is binding but not the incentive constraint. This is to say that in the equilibrium the risk neutral principal strictly prefers to use the good input rather than the bad input. With risk neutrality of the principal the distortion introduced by the fact that the regulator cannot observe x disappears.

6 Regulation Under Endogenous Contractual Organization

In all standard regulation problems, the regulator is the leader of the game in the sense of first proposing a regulatory scheme to which the principal and the agent optimally respond by agreeing on a contract. The implicit assumption so far was that P and A would always sign a contract to jointly produce the output regardless of the regulation that the EPA imposed provided they get at least their exogenous reservation utility. The EPA took this optimal response into account but could not ex-post adjust the regulatory scheme it had committed to implement. Because of the endogenous nature of the contract signed between P and A, the equivalence principle turns out to be a robust property of the optimal taxation scheme.

However, we ignored the possibility that after observing the regulatory regime, the organization of production via contracts may not survive. Instead, the parties to the contract may decide to go their separate ways and prefer to produce by themselves rather than contract.

If the regulatory agency could distinguish contract producers from independent producers, the optimal regulatory scheme would tax the parties contingently on whether they contract or independently produce. In this case, all previously obtained equivalence principles still hold.

However, if the contract producers cannot be distinguished from the independents (or if the output produced under contract cannot be disentangled from the output produced outside the contract), or if the law does not allow taxing contract producers differently from independent producers, then it becomes important to take into account that agents, after observing the regulatory scheme, may prefer to exit the contract with the principal and continue producing independently.

6.1 A Regulation Compatible with Contract Participation

One interesting possibility is the situation where the regulator may prefer contracts over independent production in the targeted industry. For example, it is conceivable that due to economies of scale in feed mixing, the marginal cost of supplying environmentally friendly feed for the integrator may be smaller than for the small independent producer. In this case the EPA would design a regulatory scheme such that it becomes incentive compatible with the endogenous choice to contract in the presence of the alternative opportunity to produce independently and pay only taxes T. The participation constraint of the agent becomes endogenous and depends on taxes T.

We say that the regulatory scheme is "contracting compatible" if, facing the regulation, agents always prefer to produce under a contract with an integrator rather than independently. If the agent produces independently his expected utility $U_a(\underline{T}, \overline{T})$ is equal to

$$U_a(\underline{T}, \overline{T}) = \max_{e \in \{\underline{e}, \overline{e}\}, x \in \{\underline{x}, \overline{x}\}} \left\{ \theta\left(x\right) \pi(e) U(\overline{q} - \overline{T} - c.\mathbf{1}_{x=\underline{x}}) + (1 - \theta\left(x\right) \pi(e)) U(\underline{q} - \underline{T} - c.\mathbf{1}_{x=\underline{x}}) - e \right\}$$

which is clearly decreasing in $\underline{T}$, $\overline{T}$.

This outside opportunity changes the agent's reservation utility in the optimal wage contract between P and A which becomes $U_0(\underline{T}, \overline{T}) = \max(U_0, U_a(\underline{T}, \overline{T}))$ but does not change the properties of the optimal contract as described in Proposition 1. According to our equivalence principle, the optimal regulation under exogenous reservation utility is always implementable whatever the taxes $\underline{T}, \overline{T}$ because only total taxes matter and increasing taxes on the agent can be compensated by the reduced taxes on the principal. Since $U_a(\underline{T}, \overline{T})$ is decreasing in $\underline{T}$ and $\overline{T}$, it is always possible to choose taxes $(\underline{T}, \overline{T})$ such that the agent's endogenous contract participation is trivially satisfied ($U_0 \geq U_a(\underline{T}, \overline{T})$). Then, one simply needs to choose taxes ($\underline{F}, \overline{F}$) such that the sum of taxes in each state is equal to the optimal taxes required by optimal regulation.

Proposition 5 ***(Non Equivalence Result - A)*** *The optimal taxation implies that for the optimal total tax revenues* ($\overline{R}^*, \underline{R}^*$)*, there exist two levels of taxation for the agent* $\underline{T}^*_{\min}$, $\overline{T}^*_{\min}$ *such that any taxation scheme* ($\underline{F}, \overline{F}, \underline{T}, \overline{T}$) *satisfying* $\underline{T} \geq \underline{T}^*_{\min}$, $\overline{T} \geq \overline{T}^*_{\min}$ *and* $\overline{F} = \overline{R}^* - \overline{T}$ *and* $\underline{F} = \underline{R}^* - \underline{T}$ *is optimal.*

Contrary to the equivalence principle obtained previously, all shares of the total taxation scheme ($\overline{R}^*, \underline{R}^*$) between the principal and the agent are no longer optimal. Instead, the optimal scheme is described by a minimal share that the agent has to pay and a maximal share that the principal has to pay.

6.2 Simultaneous Regulation of Contracts and Independent Producers

Another situation worth analyzing is the case where the EPA needs to simultaneously regulate independent producers and principal-agent contract organizations without being able to discriminate.

Consider the regulation of independent producers only. Given the optimal contract between the principal and the agent, the EPA's problem is now to maximize the expected tax revenue net of environmental damage under the incentive and participation constraints of the agent:

$$\max_{\underline{T}, \overline{T}} \theta\underline{\pi}(\overline{T} - \overline{d}) + (1 - \theta\underline{\pi})(\underline{T} - \underline{d})$$

s.t.

$$\begin{aligned} \theta\underline{\pi}U(\overline{q} - \overline{T} - c) + (1 - \theta\underline{\pi})U(\underline{q} - \underline{T} - c) - \underline{e} &\geq \theta\overline{\pi}U(\overline{q} - \overline{T} - c) + (1 - \theta\overline{\pi})U(\underline{q} - \underline{T} - c) - \overline{e} \\ \theta\underline{\pi}U(\overline{q} - \overline{T} - c) + (1 - \theta\underline{\pi})U(\underline{q} - \underline{T} - c) - \underline{e} &\geq U_0 \end{aligned}$$

with x observable. The incentive and participation constraints are binding and therefore the optimal taxes $\overline{T}^*$, $\underline{T}^*$ are uniquely determined as:

$$\begin{aligned}
\underline{T}_a^* &= \underline{T}^*\left(\overline{e}, \underline{e}, \underline{q}, c, U_0, \overline{\pi}, \underline{\pi}\right) = \underline{q} - c - U^{-1}\left(U_0 + \underline{e} + \frac{\underline{\pi}\left(\overline{e} - \underline{e}\right)}{\overline{\pi} - \underline{\pi}}\right) \\
\overline{T}_a^* &= \overline{T}^*\left(\overline{e}, \underline{e}, \overline{q}, c, U_0, \overline{\pi}, \underline{\pi}, \theta\right) = \overline{q} - c - U^{-1}\left(U_0 + \underline{e} + \frac{\underline{\pi}\left(\overline{e} - \underline{e}\right)}{\overline{\pi} - \underline{\pi}} + \frac{\overline{e} - \underline{e}}{\theta\left(\overline{\pi} - \underline{\pi}\right)}\right)
\end{aligned}$$

The previously obtained equivalence principle implies that optimal regulation can now be implemented without discrimination but in a unique way as follows:

Proposition 6 ***(Non Equivalence Result - B)*** *The optimal regulation is uniquely determined such that taxes imposed on contracting agents are also the optimal taxes to be imposed on independent producers:* $\underline{T}_a^*$, $\overline{T}_a^*$. *The optimal tax imposed on the principal is the difference between the optimal total tax revenue in each state and the optimal tax imposed on the agents, that is* $\overline{F} = \overline{R}^* - \overline{T}_a^*$ *and* $\underline{F} = \underline{R}^* - \underline{T}_a^*$.

Similar to the previous case, all shares of the total taxation scheme between the principal and the agent are no longer optimal, causing the equivalence principle to break down. Instead, an optimal division of the aggregate tax burden $(\overline{R}^*, \underline{R}^*)$ between the principal and the agent is necessary.

Notice that the optimal regulation scheme preserves the industry structure intact. This is because the taxes imposed by the EPA are such that producers will get the same expected utility regardless of whether they are contract operators or independent producers, so there is no incentive for any of them to switch to a different mode of organization.

7 Conclusion

In this paper we studied the optimal regulation of a polluting industry characterized by the prevalence of private production contracts between firms and independent agents (producers). These kinds of contractual arrangements are typically formed in animal agriculture, notably in poultry and swine industries. The main result shows that in a three-tier hierarchy (regulator-firm-agent) involving either a single-sided or a double-sided moral hazard problem, a principle of equivalence across regulatory schemes generally obtains. The equivalence principle is upset only when the effects of regulation on the endogenous organizational choices of the industry are explicitly taken into account.

We analyze two sets of informational asymmetries. First, we look at the situation where there is only a moral hazard problem on the agent's side and second where there is also a moral hazard problem on the firm's side. In both situations, for a given amount of tax revenue, the regulator can obtain the same provision of inputs and effort regardless of the tax legal incidence. Once the EPA commits to a regulatory scheme, the emerging private production contract between the firm (principal) and the producer (agent) is such that the ex-post utility levels of both parties are insensitive to the particular structure of the taxation scheme. Indeed, taxing only the principal or only the agent generates the same outcome from viewpoint of all parties. In this framework, the only task that EPA has is to determine the optimal total tax revenue in each state of nature, because any sharing of the tax burden between the principal and the agent would result in the same optimal solution. The way the optimal wage changes with respect to taxes is intimately related to the relative risk aversion of the principal and the agent. Neither double-sided moral hazard nor risk aversion impede this equivalence principle. This equivalence principle relies on the fact that the contract between the firm and the agent is optimal and endogenously determined after any change in the tax structure.

The policy implications of this equivalence principle are important. It means that the EPA can implement the optimal outcome in different ways. Indeed, the optimal outcome is attainable with subsidies for one party and taxes for the other. What really matters is the total tax revenue and not the particular levels of taxes or subsidies levied on each party. However, the optimal total tax revenue that must be imposed on the contractual organization depends itself on the preferences of both parties, on their reservation utilities, and the parameters of the cost and production functions.

In the CARA case, comparative statics results are much easier to derive. In this case, the principal gets full insurance (same utility levels in high and low state of nature) when the provision of input is observable. When the provision of input is not observable, the principal has to bear part of the risk due to incentives that will induce him to use the good input.

Of course, if the EPA values the tax revenue collected from the principal and the agent differently (because of different administrative and enforcement costs), then the equivalence between taxing only the agent or only the firm or both would disappear. The optimal regulatory scheme would require to place the full tax burden on the party for which tax collection is the least expensive. Also, any rigidity in the implementation of the optimal contract between the firm and the agent would invalidate the equivalence principle. This could follow, for instance, from possible limited liability constraints of the agent. Except for these kinds of constraints, the equivalence principle is in general quite robust and means that the share of taxes between parties is neutral regarding the outcome sought by the regulator. Therefore, extending taxation of polluting goods to contractors will have an effect only if the total tax revenue changes.

Finally, we also consider that the industry organizational choices may be endogenous to the EPA's regulation. In such cases, the equivalence principle breaks down. For example, when producers can decide to produce independently given the taxes they face, the agent's participation constraint becomes endogenous and the regulatory scheme of the EPA has to be compatible with the incentives to contract. Contrary to the equivalence principle, the optimal taxation requires some minimal and maximal shares that the agent and the principal have to pay. Also, in market structures characterized by the coexistence of independent producers and contract operators, if the EPA is unable or unwilling to discriminate between them, an optimal division of the aggregate tax burden between the principal and the agent is necessary to implement the optimal outcome. In this case the optimal regulation consists of taxing contracting agents by the same optimal tax necessary in the regulation of independent producers. The optimal tax for the principal is then the difference between the optimal total tax revenue and the tax imposed on agents. With such a taxation, producers are indifferent between the two organizational structures and regulation does not affect the endogenous vertical organization of the industry.

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Appendix

A Optimal regulation under single moral hazard and no conflict of interest on effort

The case with no conflict of interest between the regulator and the principal is the situation where the EPA wants to implement high effort level $\overline{e}$, which is the same effort level that P would want to implement without any regulatory pressure. In this case the EPA only wants to extract the principal's surplus:

$$\begin{array}{ll} \max_{\underline{w},\overline{w}} \theta\overline{\pi}V(\overline{q}-\overline{F}-\overline{w}-c)+(1-\theta\overline{\pi})V(\underline{q}-\underline{F}-\underline{w}-c) & \\ s.t.\ \theta\overline{\pi}U(\overline{w}-\overline{T})+(1-\theta\overline{\pi})U(\underline{w}-\underline{T})-\overline{e}\geq U_0 & (\mu) \\ \theta\overline{\pi}U(\overline{w}-\overline{T})+(1-\theta\overline{\pi})U(\underline{w}-\underline{T})-\overline{e}\geq \theta\underline{\pi}U(\overline{w}-\overline{T})+(1-\theta\underline{\pi})U(\underline{w}-\underline{T})-\underline{e} & (\lambda) \end{array} \tag{16}$$

where μ and λ are Lagrange multipliers associated to the participation and incentive constraints. First order conditions give

$$\begin{aligned} \lambda &= \frac{\overline{\pi}(1-\theta\overline{\pi})}{\overline{\pi}-\underline{\pi}}\frac{\underline{U}'\overline{V}'-\underline{V}'\overline{U}'}{\overline{U}'\underline{U}'} \\ \mu &= \frac{\theta\overline{\pi}\underline{U}'\overline{V}'+(1-\theta\overline{\pi})\underline{V}'\overline{U}'}{\overline{U}'\underline{U}'} = \frac{\theta(\overline{\pi}-\underline{\pi})}{1-\theta\overline{\pi}}\lambda+\frac{\underline{V}'}{\underline{U}'}>0 \end{aligned}$$

The participation constraint is binding because $\mu > 0$. Then, either the incentive constraint is binding or it is not. If the incentive constraint is not binding, we get the result

$$\frac{\overline{V}'}{\underline{V}'}=\frac{\overline{U}'}{\underline{U}'}$$

pointing towards the perfect risk sharing between P and A. The optimal wages $\overline{w}_0(\overline{F},\overline{T})$ and $\underline{w}_0(\underline{F},\underline{T})$ satisfy

$$\frac{V'(\overline{q}-\overline{F}-\overline{w}_0(\overline{F},\overline{T})-c)}{V'(\underline{q}-\underline{F}-\underline{w}_0(\underline{F},\underline{T})-c)}=\frac{U'(\overline{w}_0(\overline{F},\overline{T})-\overline{T})}{U'(\underline{w}_0(\underline{F},\underline{T})-\underline{T})}$$

If the incentive constraint is binding, i.e. $\lambda > 0$, we obtain

$$\frac{\overline{V}'}{\underline{V}'}>\frac{\overline{U}'}{\underline{U}'} \tag{17}$$

which is the same result as the one obtained in the benchmark case with no regulation despite the fact that the optimal solution is different. Similar to the benchmark case with CARA utilities, the gap between wages in good and bad states is increased compared to the perfect risk sharing case.

Next, it is also obvious that Proposition 1 is also valid in the no conflict case regardless of whether the incentive constraint is binding or not. Assuming the incentive constraint is binding (that is $\lambda > 0$), we obtain

$$\begin{aligned} \underline{U} &= U_0 + \frac{\overline{\pi}\underline{e} - \underline{\pi}\overline{e}}{\overline{\pi} - \underline{\pi}} \\ \overline{U} &= \underline{U} + \frac{\overline{e} - \underline{e}}{\theta(\overline{\pi} - \underline{\pi})} > \underline{U} \end{aligned}$$

It follows that the agent's levels of utility are the same in each state with or without conflict of interest about effort and is a function of model parameters ($U(.)$, U_0, $\overline{e}$, $\underline{e}$, $\overline{\pi}$, $\underline{\pi}$, θ). Moreover, the agent's ratio of marginal utilities in each state is always the same in both cases. Consequently, we can order the ratio of marginal utilities of the principal and the agent in case of conflict of interest compared to the no conflict case:

$$\frac{\overline{V}'^{*nc}}{\underline{V}'^{*nc}} > \frac{\overline{U}'^{*nc}}{\underline{U}'^{*nc}} = \frac{\overline{U}'^{*c}}{\underline{U}'^{*c}} > \frac{\overline{V}'^{*c}}{\underline{V}'^{*c}}$$

where subscript ^{nc} corresponds to the case where $\overline{e}$ is implemented and ^{c} when $\underline{e}$ is implemented.

In the second step of the solution procedure the EPA's problem is very similar to the conflict of interest case presented in Section 4.2. The solution to the program yields the same conditions as in (12), (13). More precisely, the EPA's problem can be written as

$$\begin{aligned} &\max_{\underline{F},\overline{F},\underline{T},\overline{T}} \theta\overline{\pi}(\overline{F} + \overline{T} - \overline{d}) + (1 - \theta\overline{\pi})(\underline{F} + \underline{T} - \underline{d}) \\ &s.t.\ \theta\overline{\pi}\overline{V}^* + (1 - \theta\overline{\pi})\underline{V}^* \geq V_0 \qquad (\eta) \end{aligned} \tag{18}$$

where $\overline{V}^* = V(\overline{q} - \overline{F} - \overline{w}^* - c)$, $\underline{V}^* = V(\underline{q} - \underline{F} - \underline{w}^* - c)$, and $\overline{w}^*$ and $\underline{w}^*$ are solutions of (16).

The program being concave, first order conditions are sufficient

$$\begin{aligned}
\theta\overline{\pi} &= \eta\{\theta\overline{\pi}(1+\frac{\partial\overline{w}^*}{\partial\overline{F}})\overline{V}^{*\prime} + (1-\theta\overline{\pi})\frac{\partial\underline{w}^*}{\partial\overline{F}}\underline{V}^{*\prime}\} && (19)\\
1-\theta\overline{\pi} &= \eta\{\overline{\pi}\frac{\partial\overline{w}^*}{\partial\underline{F}}\overline{V}^{*\prime} + (1-\theta\overline{\pi})(1+\frac{\partial\underline{w}^*}{\partial\underline{F}})\underline{V}^{*\prime}\} && (20)\\
\theta\overline{\pi} &= \eta\{\theta\overline{\pi}\frac{\partial\overline{w}^*}{\partial\overline{T}}\overline{V}^{*\prime} + (1-\theta\overline{\pi})\frac{\partial\underline{w}^*}{\partial\overline{T}}\underline{V}^{*\prime}\} && (21)\\
1-\theta\overline{\pi} &= \eta\{\theta\overline{\pi}\frac{\partial\overline{w}^*}{\partial\underline{T}}\overline{V}^{*\prime} + (1-\theta\overline{\pi})\frac{\partial\underline{w}^*}{\partial\underline{T}}\underline{V}^{*\prime}\} && (22)
\end{aligned}$$

Using conditions (4) and (5) into (19)-(22) we get

$$\begin{aligned}
(1+\frac{\partial\overline{w}^*}{\partial\overline{F}})\overline{V}^{*\prime} &= (1+\frac{\partial\underline{w}^*}{\partial\underline{F}})\underline{V}^{*\prime} = \frac{\partial\overline{w}^*}{\partial\overline{T}}\overline{V}^{*\prime} = \frac{\partial\underline{w}^*}{\partial\underline{T}}\underline{V}^{*\prime}\\
\eta &= \frac{1}{\frac{\overline{\sigma}_U}{\overline{\sigma}_V+\overline{\sigma}_U}\overline{V}^{*\prime}} > 0
\end{aligned}$$

The participation constraint of (18) is binding because $\eta > 0$ and we get the additional condition

$$\frac{\overline{V}^{*\prime}}{\underline{V}^{*\prime}} = \frac{\frac{\partial\underline{w}^*}{\partial\underline{T}}}{\frac{\partial\overline{w}^*}{\partial\overline{T}}} = \frac{\underline{\sigma}_U}{\overline{\sigma}_U}\frac{\overline{\sigma}_U+\overline{\sigma}_V}{\underline{\sigma}_U+\underline{\sigma}_V}$$

which characterizes the ratio of marginal utilities at the optimum.

With CARA utility functions,

$$\frac{\overline{V}^{*\prime}}{\underline{V}^{*\prime}} = \exp -\sigma_V[\overline{q}-\underline{q}-(\overline{F}-\underline{F})-(\overline{w}^*-\underline{w}^*)] = 1$$

hence

$$\begin{aligned}
\overline{q}-\underline{q} &= (\overline{F}-\underline{F}) + (\overline{w}^*(\overline{F},\overline{T}) - \underline{w}^*(\underline{F},\underline{T}))\\
\overline{q}-\underline{q} &= \frac{\sigma_U}{\sigma_U+\sigma_V}[(\overline{F}+\overline{T})-(\underline{F}+\underline{T})] + \overline{w}^*(0,0) - \underline{w}^*(0,0)
\end{aligned}$$

B Optimal regulation under double moral hazard and no conflict of interest on effort

Consider the case where EPA chooses taxes such that P wants to implement $\overline{e}$ and $\underline{x}$. The principal's program is the same as in section A where x is observable:

$$\begin{aligned}
&\max_{\underline{w},\overline{w}} \overline{\pi}\theta V(\overline{q}-\overline{F}-\overline{w}-c) + (1-\overline{\pi}\theta)V(\underline{q}-\underline{F}-\underline{w}-c)\\
&s.t.\ \overline{\pi}\theta U(\overline{w}-\overline{T}) + (1-\overline{\pi}\theta)U(\underline{w}-\underline{T}) - \overline{e} \geq U_0 && (\mu)\\
&\overline{\pi}\theta U(\overline{w}-\overline{T}) + (1-\overline{\pi}\theta)U(\underline{w}-\underline{T}) - \overline{e} \geq \underline{\pi}\theta U(\overline{w}-\overline{T}) + (1-\underline{\pi}\theta)U(\underline{w}-\underline{T}) - \underline{e} && (\lambda)
\end{aligned}$$

Proposition 1 is valid and so are the other results of sub-section 4.1.

The EPA's problem now becomes

$$\begin{array}{ll}\max\limits_{\underline{F},\overline{F},\underline{T},\overline{T}} \theta\overline{\pi}(\overline{F}+\overline{T}-\overline{d})+(1-\theta\overline{\pi})(\underline{F}+\underline{T}-\underline{d}) & \\ s.t.\ \theta\overline{\pi}\overline{V}^{**}+(1-\theta\overline{\pi})\underline{V}^{**}\geq V_0 & (\eta) \\ \theta\overline{\pi}\overline{V}^{**}+(1-\theta\overline{\pi})\underline{V}^{**}\geq \overline{\pi}\overline{V}^{*}+(1-\overline{\pi})\underline{V}^{*} & (\gamma)\end{array}$$

where $\overline{V}^{**}=V(\overline{q}-\overline{F}-\overline{w}^{**}-c)$, $\underline{V}^{**}=V(\underline{q}-\underline{F}-\underline{w}^{**}-c)$, where $\overline{w}^{**}$ and $\underline{w}^{**}$ are solutions of (1), and $\overline{V}^{*}=V(\overline{q}-\overline{F}-\overline{w}^{*})$, $\underline{V}^{*}=V(\underline{q}-\underline{F}-\underline{w}^{*})$, and wages $\overline{w}^{*}$ and $\underline{w}^{*}$ are solutions of P's problem when EPA's regulates production without taking into account incentives to choose good input, that is, are the same wage functions as in Proposition 1 with $c=0$.

Proposition 7 *The ratio of marginal effect of taxes T on P's utility in high and low states satisfies the following conditions*

$$\frac{\frac{d\overline{V}^{**}}{d\overline{T}}}{\frac{d\underline{V}^{**}}{d\underline{T}}}=\frac{\frac{d\overline{V}^{**}}{d\overline{F}}}{\frac{d\underline{V}^{**}}{d\underline{F}}}=\left(\frac{\theta(1-\overline{\pi})}{1-\theta\overline{\pi}}+\frac{\theta(1-\theta)}{(1-\theta\overline{\pi})(\theta+\gamma\overline{V}^{*\prime}\frac{\partial\overline{w}^{*}}{\partial\overline{T}})}\right)^{-1}$$

$$1\leq\frac{\frac{d\overline{V}^{**}}{d\overline{T}}}{\frac{d\underline{V}^{**}}{d\underline{T}}}=\frac{\frac{\partial\overline{w}^{**}}{\partial\overline{T}}\overline{V}^{**\prime}}{\frac{\partial\underline{w}^{**}}{\partial\underline{T}}\underline{V}^{**\prime}}<\frac{1-\theta\overline{\pi}}{\theta(1-\overline{\pi})}$$

that is the ratio of marginal utilities satisfies

$$\frac{\underline{\sigma}_U^{**}}{\overline{\sigma}_U^{**}}\frac{\overline{\sigma}_U^{**}+\overline{\sigma}_V^{**}}{\underline{\sigma}_U^{**}+\underline{\sigma}_V^{**}}\leq\frac{\overline{V}^{**\prime}}{\underline{V}^{**\prime}}<\frac{1-\theta\overline{\pi}}{\theta(1-\overline{\pi})}\frac{\underline{\sigma}_U^{**}}{\overline{\sigma}_U^{**}}\frac{\overline{\sigma}_U^{**}+\overline{\sigma}_V^{**}}{\underline{\sigma}_U^{**}+\underline{\sigma}_V^{**}}$$

Proof. The program being concave, first order conditions are sufficient

$$\begin{aligned}\theta\overline{\pi} &= (\eta+\gamma)\{\theta\overline{\pi}(1+\frac{\partial\overline{w}^{**}}{\partial\overline{F}})\overline{V}^{**\prime}+(1-\theta\overline{\pi})\frac{\partial\underline{w}^{**}}{\partial\overline{F}}\underline{V}^{**\prime}\} \\ &\quad -\gamma\{\overline{\pi}\overline{V}^{*\prime}(1+\frac{\partial\overline{w}^{*}}{\partial\overline{F}})+(1-\overline{\pi})\underline{V}^{*\prime}\frac{\partial\underline{w}^{*}}{\partial\overline{F}}\} \\ 1-\theta\overline{\pi} &= (\eta+\gamma)\{\theta\overline{\pi}\frac{\partial\overline{w}^{**}}{\partial\underline{F}}\overline{V}^{**\prime}+(1-\theta\overline{\pi})(1+\frac{\partial\underline{w}^{**}}{\partial\underline{F}})\underline{V}^{**\prime}\} \\ &\quad -\gamma\{\overline{\pi}\overline{V}^{*\prime}\frac{\partial\overline{w}^{*}}{\partial\underline{F}}+(1-\overline{\pi})\underline{V}^{*\prime}(1+\frac{\partial\underline{w}^{*}}{\partial\underline{F}})\} \\ \theta\overline{\pi} &= (\eta+\gamma)\{\theta\overline{\pi}\frac{\partial\overline{w}^{**}}{\partial\overline{T}}\overline{V}^{**\prime}+(1-\theta\overline{\pi})\frac{\partial\underline{w}^{**}}{\partial\overline{T}}\underline{V}^{**\prime}\} \\ &\quad -\gamma\{\overline{\pi}\frac{\partial\overline{w}^{*}}{\partial\overline{T}}\overline{V}^{*\prime}+(1-\overline{\pi})\frac{\partial\underline{w}^{*}}{\partial\overline{T}}\underline{V}^{*\prime}\} \\ 1-\theta\overline{\pi} &= (\eta+\gamma)\{\theta\overline{\pi}\frac{\partial\overline{w}^{**}}{\partial\underline{T}}\overline{V}^{**\prime}+(1-\theta\overline{\pi})\frac{\partial\underline{w}^{**}}{\partial\underline{T}}\underline{V}^{**\prime}\} \\ &\quad -\gamma\{\overline{\pi}\frac{\partial\overline{w}^{*}}{\partial\underline{T}}\overline{V}^{*\prime}+(1-\overline{\pi})\frac{\partial\underline{w}^{*}}{\partial\underline{T}}\underline{V}^{*\prime}\}\end{aligned}$$

From proposition 1 we know that $\frac{\partial \overline{w}^*}{\partial \underline{F}} = \frac{\partial \overline{w}^*}{\partial \underline{T}} = \frac{\partial \underline{w}^*}{\partial \overline{F}} = \frac{\partial \underline{w}^*}{\partial \overline{T}} = 0$, $1 + \frac{\partial \overline{w}^{**}}{\partial \overline{F}} - \frac{\partial \overline{w}^{**}}{\partial \overline{T}} = 1 + \frac{\partial \underline{w}^{**}}{\partial \underline{F}} - \frac{\partial \underline{w}^{**}}{\partial \underline{T}} = 0$, and $1 + \frac{\partial \overline{w}^*}{\partial \overline{F}} - \frac{\partial \overline{w}^*}{\partial \overline{T}} = 1 + \frac{\partial \underline{w}^*}{\partial \underline{F}} - \frac{\partial \underline{w}^*}{\partial \underline{T}} = 0$. Therefore constraints (23) and (25) are the same, and (24) and (26) are the same. Simplifying, we get

$$\begin{aligned} \theta &= (\eta+\gamma)\theta \frac{\partial \overline{w}^{**}}{\partial \overline{T}} \overline{V}^{**\prime} - \gamma \overline{V}^{*\prime} \frac{\partial \overline{w}^*}{\partial \overline{T}} \\ 1-\theta\overline{\pi} &= (\eta+\gamma)(1-\theta\overline{\pi}) \frac{\partial \underline{w}^{**}}{\partial \underline{T}} \underline{V}^{**\prime} - \gamma(1-\overline{\pi}) \underline{V}^{*\prime} \frac{\partial \underline{w}^*}{\partial \underline{T}} \end{aligned}$$

Using $\frac{\partial \overline{w}^*}{\partial \overline{T}} \overline{V}^{*\prime} = \frac{\partial \underline{w}^*}{\partial \underline{T}} \underline{V}^{*\prime}$, we get

$$\begin{aligned} \eta+\gamma &= \frac{1-\theta}{(1-\theta\overline{\pi})\frac{\partial \underline{w}^{**}}{\partial \underline{T}} \underline{V}^{**\prime} - \theta(1-\overline{\pi})\frac{\partial \overline{w}^{**}}{\partial \overline{T}} \overline{V}^{**\prime}} \\ \gamma &= \frac{\frac{\partial \underline{w}^{**}}{\partial \underline{T}} \underline{V}^{**\prime} - \frac{\partial \overline{w}^{**}}{\partial \overline{T}} \overline{V}^{**\prime}}{\theta(1-\overline{\pi})\frac{\partial \overline{w}^{**}}{\partial \overline{T}} \overline{V}^{**\prime} - (1-\theta\overline{\pi})\frac{\partial \underline{w}^{**}}{\partial \underline{T}} \underline{V}^{**\prime}} \frac{\theta(1-\theta\overline{\pi})}{\frac{\partial \overline{w}^*}{\partial \overline{T}} \overline{V}^{*\prime}} \end{aligned}$$

That is

$$\eta = \frac{\theta(1-\theta\overline{\pi})(\frac{\partial \underline{w}^{**}}{\partial \underline{T}} \underline{V}^{**\prime} - \frac{\partial \overline{w}^{**}}{\partial \overline{T}} \overline{V}^{**\prime}) + (1-\theta)\frac{\partial \overline{w}^*}{\partial \overline{T}} \overline{V}^{*\prime}}{[(1-\theta\overline{\pi})\frac{\partial \underline{w}^{**}}{\partial \underline{T}} \underline{V}^{**\prime} - \theta(1-\overline{\pi})\frac{\partial \overline{w}^{**}}{\partial \overline{T}} \overline{V}^{**\prime}]\frac{\partial \overline{w}^*}{\partial \overline{T}} \overline{V}^{*\prime}}$$

As $\theta(1-\overline{\pi}) < (1-\theta\overline{\pi})$, if $\frac{\partial \underline{w}^{**}}{\partial \underline{T}} \underline{V}^{**\prime} > \frac{\partial \overline{w}^{**}}{\partial \overline{T}} \overline{V}^{**\prime}$, then $(1-\overline{\pi})\theta \frac{\partial \overline{w}^{**}}{\partial \overline{T}} \overline{V}^{**\prime} < (1-\theta\overline{\pi})\frac{\partial \underline{w}^{**}}{\partial \underline{T}} \underline{V}^{**\prime}$, implying $\gamma < 0$, which is not possible. Therefore $\frac{\partial \underline{w}^{**}}{\partial \underline{T}} \underline{V}^{**\prime} < \frac{\partial \overline{w}^{**}}{\partial \overline{T}} \overline{V}^{**\prime}$. In addition to get $\gamma \geq 0$, it must be that $(1-\overline{\pi})\theta \frac{\partial \overline{w}^{**}}{\partial \overline{T}} \overline{V}^{**\prime} < (1-\theta\overline{\pi})\frac{\partial \underline{w}^{**}}{\partial \underline{T}} \underline{V}^{**\prime}$.
We have $\frac{\frac{\partial \underline{w}^{**}}{\partial \underline{T}} \underline{V}^{**\prime}}{\frac{\partial \overline{w}^{**}}{\partial \overline{T}} \overline{V}^{**\prime}} = \frac{\theta(1-\overline{\pi})}{1-\theta\overline{\pi}} - \frac{\theta(\theta-1)}{(1-\theta\overline{\pi})(\theta+\gamma\overline{V}^{*\prime}\frac{\partial \overline{w}^*}{\partial \overline{T}})}$ and then

$$\frac{\overline{V}^{**\prime}}{\underline{V}^{**\prime}} = \frac{\frac{\partial \underline{w}^{**}}{\partial \underline{T}}}{\frac{\partial \overline{w}^{**}}{\partial \overline{T}}} \left(\frac{\theta(1-\overline{\pi})}{1-\theta\overline{\pi}} + \frac{\theta(1-\theta)}{(1-\theta\overline{\pi})(\theta+\gamma\overline{V}^{*\prime}\frac{\partial \overline{w}^*}{\partial \overline{T}})} \right)^{-1} > \frac{\frac{\partial \underline{w}^{**}}{\partial \underline{T}}}{\frac{\partial \overline{w}^{**}}{\partial \overline{T}}} = \frac{\underline{\sigma}_U^{**}}{\overline{\sigma}_U^{**}} \frac{\overline{\sigma}_U^{**}+\overline{\sigma}_V^{**}}{\underline{\sigma}_U^{**}+\underline{\sigma}_V^{**}}$$

■

The economic intuition behind Proposition 7 is the same as in Proposition 4, except for the fact that the ratio of probabilities $\frac{\theta(1-\overline{\pi})}{1-\theta\overline{\pi}} = \frac{P(\overline{q}|\overline{e},\underline{x})}{P(\overline{q}|\overline{e},\overline{x})}\frac{P(\underline{q}|\overline{e},\overline{x})}{P(\underline{q}|\overline{e},\underline{x})} > 1$ is different due to the change in the effort regime. The other results carry over completely to the no-conflict case.

C Proof of Proposition 1

To get the partial derivatives of $\overline{w}^*$ and $\underline{w}^*$ with respect to $\underline{F}$, $\overline{F}$, $\underline{T}$, $\overline{T}$, we differentiate the first order conditions with respect to $\underline{F}$, $\overline{F}$, $\underline{T}$, $\overline{T}$ and use them to replace λ and μ.

$$\begin{aligned}
\frac{\partial \overline{w}^*}{\partial \overline{F}} &= \frac{-\underline{\pi}\overline{V}''}{\underline{\pi}\overline{V}'' + [\lambda(\underline{\pi}-\overline{\pi}) + \mu\underline{\pi}]\overline{U}''} = -\frac{-\overline{V}''/\overline{V}'}{-\overline{V}''/\overline{V}' - \overline{U}''/\overline{U}'} \\
\frac{\partial \overline{w}^*}{\partial \overline{T}} &= \frac{[\lambda(\underline{\pi}-\overline{\pi}) + \mu\underline{\pi}]\overline{U}''}{\underline{\pi}\overline{V}'' + [\lambda(\underline{\pi}-\overline{\pi}) + \mu\underline{\pi}]\overline{U}''} = \frac{-\overline{U}''/\overline{U}'}{-\overline{V}''/\overline{V}' - \overline{U}''/\overline{U}'} \\
\frac{\partial \overline{w}^*}{\partial \underline{F}} &= \frac{\partial \overline{w}^*}{\partial \underline{T}} = 0 \\
\frac{\partial \underline{w}^*}{\partial \underline{F}} &= \frac{-(1-\theta\underline{\pi})\underline{V}''}{[\lambda\theta(\overline{\pi}-\underline{\pi}) + \mu(1-\theta\underline{\pi})]\underline{U}'' + (1-\theta\underline{\pi})\underline{V}''} = -\frac{-\underline{V}''/\underline{V}'}{-\underline{U}''/\underline{U}' - \underline{V}''/\underline{V}'} \\
\frac{\partial \underline{w}^*}{\partial \underline{T}} &= \frac{[\lambda\theta(\overline{\pi}-\underline{\pi}) + \mu(1-\theta\underline{\pi})]\underline{U}''}{(1-\theta\underline{\pi})\underline{V}'' + [\lambda\theta(\overline{\pi}-\underline{\pi}) + \mu(1-\theta\underline{\pi})]\underline{U}''} = \frac{-\underline{U}''/\underline{U}'}{-\underline{V}''/\underline{V}' - \underline{U}''/\underline{U}'} \\
\frac{\partial \underline{w}^*}{\partial \overline{F}} &= \frac{\partial \underline{w}^*}{\partial \overline{T}} = 0
\end{aligned}$$

D Proof of Proposition 2

Given a taxation scheme $\overline{T}$, $\overline{F}$, $\underline{T}$, $\underline{F}$, denote $\overline{w}^*$, $\underline{w}^*$ solution of (1) and assume that the EPA can choose $\overline{T}'$, $\overline{F}'$, $\underline{T}'$, $\underline{F}'$ such that $\overline{T}' + \overline{F}' = \overline{T} + \overline{F}$ and $\underline{T}' + \underline{F}' = \underline{T} + \underline{F}$. Then, the principal can set wages $\overline{w}'^*$, $\underline{w}'^*$ such that $\overline{w}'^* - \overline{T}' = \overline{w}^* - \overline{T}$ and $\overline{F}' + \overline{w}'^* = \overline{F} + \overline{w}^*$, which is possible because $\overline{T}' + \overline{F}' = \overline{T} + \overline{F}$. Then, it is clear from (1) that the participation and incentive constraints are unchanged (because ex-post utility levels are unchanged) and the principal's objective is the same. Therefore, $(\overline{w}'^*, \underline{w}'^*, \overline{T}', \overline{F}', \underline{T}', \underline{F}')$ implements the same outcome as $(\overline{w}^*, \underline{w}^*, \overline{T}, \overline{F}, \underline{T}, \underline{F})$. Actually, taxes F and T are perfect substitutes in the EPA's objective (only total taxes matter), wages w and taxes F are also perfect substitutes in the principal's objective, and optimal wages chosen by P are such that net wages $(w-T)$ of the agent are constant (do not depend on taxes F and T). Therefore, the same outcome can be implemented with $\overline{T} = \underline{T} = 0$ or $\underline{F} = \overline{F} = 0$ (in fact, there is an infinity of solutions in $(\underline{F}, \overline{F}, \underline{T}, \overline{T})$ including the cases where $\underline{F} = \overline{F} = 0$ or $\underline{T} = \overline{T} = 0$). Therefore, EPA's regulation problem can be written as

$$\max_{\underline{R},\overline{R}} \theta\underline{\pi}(\overline{R}-\overline{d})+(1-\theta\underline{\pi})(\underline{R}-\underline{d})$$
$$s.t.\ \theta\underline{\pi}\overline{V}^{*}+(1-\theta\underline{\pi})\underline{V}^{*}\geq V_0 \qquad (\eta)$$

where $\overline{V}^{*}=V(\overline{q}-\overline{\gamma}^{*}(\overline{R})-c)$, $\underline{V}^{*}=V(\underline{q}-\underline{\gamma}^{*}(\underline{R})-c)$, $\overline{\gamma}^{*}(\overline{R})=\overline{w}^{*}(\overline{F},\overline{T})+\overline{F}$, and $\underline{\gamma}^{*}(\underline{R})=\underline{F}+\underline{w}^{*}(\underline{F},\underline{T})$ are total charges, $\overline{w}^{*}(\overline{F},\overline{T})$ and $\underline{w}^{*}(\underline{F},\underline{T})$ are solutions to (1).

E Proof of Corollary 3

The proof is similar as in section D except that now the EPA's program has an additional incentive constraint. However, it is clear, with the same arguments on the optimal wage contract between P and A which keeps the same properties, that given a taxation scheme $\overline{T}$, $\overline{F}$, $\underline{T}$, $\underline{F}$, the EPA can choose $\overline{T}^{'}$, $\overline{F}^{'}$, $\underline{T}'$, $\underline{F}'$ such that $\overline{T}^{'}+\overline{F}^{'}=\overline{T}+\overline{F}$ and $\underline{T}'+\underline{F}'=\underline{T}+\underline{F}$ without changing any of the net utility levels of P and A. The participation and incentive constraints of A are unchanged (because ex-post utility levels are unchanged) and the principal's objective is the same. Moreover, $\overline{V}^{*}$, $\underline{V}^{*}$, $\overline{V}^{**}$, $\underline{V}^{**}$ are unchanged with $(\overline{T},\overline{F},\underline{T},\underline{F})$ or $(\overline{T}^{'},\overline{F}^{'},\underline{T}',\underline{F}')$. This implies also that the Lagrange multipliers γ and η will not change and EPA's regulation problem can be written as function of total taxes only

$$\max_{\underline{R},\overline{R}} \theta\underline{\pi}(\overline{R}-\overline{d})+(1-\theta\underline{\pi})(\underline{R}-\underline{d})$$
$$s.t.\ \theta\underline{\pi}\overline{V}^{**}+(1-\theta\underline{\pi})\underline{V}^{**}\geq V_0 \qquad (\eta)$$
$$\theta\underline{\pi}\overline{V}^{**}+(1-\theta\underline{\pi})\underline{V}^{**}\geq \underline{\pi}\overline{V}^{*}+(1-\underline{\pi})\underline{V}^{*} \qquad (\gamma)$$

F Proof of Proposition 4

The program being concave, first order conditions are sufficient

$$\begin{aligned}
\theta\underline{\pi} &= (\eta+\gamma)\{\theta\underline{\pi}(1+\frac{\partial\overline{w}^{**}}{\partial\overline{F}})\overline{V}^{**\prime} + (1-\theta\underline{\pi})\frac{\partial\underline{w}^{**}}{\partial\overline{F}}\underline{V}^{**\prime}\} && (23)\\
&\quad -\gamma\{\underline{\pi}(1+\frac{\partial\overline{w}^{*}}{\partial\overline{F}})\overline{V}^{*\prime} + (1-\underline{\pi})\frac{\partial\underline{w}^{*}}{\partial\overline{F}}\underline{V}^{*\prime}\}\\
1-\theta\underline{\pi} &= (\eta+\gamma)\{\theta\underline{\pi}\frac{\partial\overline{w}^{**}}{\partial\underline{F}}\overline{V}^{**\prime} + (1-\theta\underline{\pi})(1+\frac{\partial\underline{w}^{**}}{\partial\underline{F}})\underline{V}^{**\prime}\} && (24)\\
&\quad -\gamma\{\underline{\pi}\frac{\partial\overline{w}^{*}}{\partial\underline{F}}\overline{V}^{*\prime} + (1-\underline{\pi})(1+\frac{\partial\underline{w}^{*}}{\partial\underline{F}})\underline{V}^{*\prime}\}\\
\theta\underline{\pi} &= (\eta+\gamma)\{\theta\underline{\pi}\frac{\partial\overline{w}^{**}}{\partial\overline{T}}\overline{V}^{**\prime} + (1-\theta\underline{\pi})\frac{\partial\underline{w}^{**}}{\partial\overline{T}}\underline{V}^{**\prime}\} && (25)\\
&\quad -\gamma\{\underline{\pi}\frac{\partial\overline{w}^{*}}{\partial\overline{T}}\overline{V}^{*\prime} + (1-\underline{\pi})\frac{\partial\underline{w}^{*}}{\partial\overline{T}}\underline{V}^{*\prime}\}\\
1-\theta\underline{\pi} &= (\eta+\gamma)\{\theta\underline{\pi}\frac{\partial\overline{w}^{**}}{\partial\underline{T}}\overline{V}^{**\prime} + (1-\theta\underline{\pi})\frac{\partial\underline{w}^{**}}{\partial\underline{T}}\underline{V}^{**\prime}\} && (26)\\
&\quad -\gamma\{\underline{\pi}\frac{\partial\overline{w}^{*}}{\partial\underline{T}}\overline{V}^{*\prime} + (1-\underline{\pi})\frac{\partial\underline{w}^{*}}{\partial\underline{T}}\underline{V}^{*\prime}\}
\end{aligned}$$

From proposition 1 we know that $\frac{\partial\overline{w}^{*}}{\partial\underline{F}} = \frac{\partial\overline{w}^{*}}{\partial\underline{T}} = \frac{\partial\underline{w}^{*}}{\partial\overline{F}} = \frac{\partial\underline{w}^{*}}{\partial\overline{T}} = 0$, $\frac{\partial\overline{w}^{**}}{\partial\underline{F}} = \frac{\partial\overline{w}^{**}}{\partial\underline{T}} = \frac{\partial\underline{w}^{**}}{\partial\overline{F}} = \frac{\partial\underline{w}^{**}}{\partial\overline{T}} = 0$, $\frac{\partial\overline{w}^{**}}{\partial\overline{F}} - \frac{\partial\overline{w}^{**}}{\partial\overline{T}} = \frac{\partial\underline{w}^{**}}{\partial\underline{F}} - \frac{\partial\underline{w}^{**}}{\partial\underline{T}} = -1$ and $\frac{\partial\overline{w}^{*}}{\partial\overline{F}} - \frac{\partial\overline{w}^{*}}{\partial\overline{T}} = \frac{\partial\underline{w}^{*}}{\partial\underline{F}} - \frac{\partial\underline{w}^{*}}{\partial\underline{T}} = -1$ therefore constraints (23) and (25) are the same and (24) and (26) are the same. Simplifying, we get

$$\begin{aligned}
\theta &= (\eta+\gamma)\theta\frac{\partial\overline{w}^{**}}{\partial\overline{T}}\overline{V}^{**\prime} - \gamma\frac{\partial\overline{w}^{*}}{\partial\overline{T}}\overline{V}^{*\prime}\\
1-\theta\underline{\pi} &= (\eta+\gamma)(1-\theta\underline{\pi})\frac{\partial\underline{w}^{**}}{\partial\underline{T}}\underline{V}^{**\prime} - \gamma(1-\underline{\pi})\frac{\partial\underline{w}^{*}}{\partial\underline{T}}\underline{V}^{*\prime}
\end{aligned}$$

Using also $\frac{\partial\overline{w}^{*}}{\partial\overline{T}}\overline{V}^{*\prime} = \frac{\partial\underline{w}^{*}}{\partial\underline{T}}\underline{V}^{*\prime}$, we get

$$\begin{aligned}
\eta+\gamma &= \frac{1-\theta}{(1-\theta\underline{\pi})\frac{\partial\underline{w}^{**}}{\partial\underline{T}}\underline{V}^{**\prime} - \theta(1-\underline{\pi})\frac{\partial\overline{w}^{**}}{\partial\overline{T}}\overline{V}^{**\prime}}\\
\gamma &= \frac{\frac{\partial\underline{w}^{**}}{\partial\underline{T}}\underline{V}^{**\prime} - \frac{\partial\overline{w}^{**}}{\partial\overline{T}}\overline{V}^{**\prime}}{\theta(1-\underline{\pi})\frac{\partial\overline{w}^{**}}{\partial\overline{T}}\overline{V}^{**\prime} - (1-\theta\underline{\pi})\frac{\partial\underline{w}^{**}}{\partial\underline{T}}\underline{V}^{**\prime}}\,\frac{\theta(1-\theta\underline{\pi})}{\frac{\partial\overline{w}^{*}}{\partial\overline{T}}\overline{V}^{*\prime}}
\end{aligned}$$

That is

$$\eta = \frac{\theta(1-\theta\underline{\pi})(\frac{\partial\underline{w}^{**}}{\partial\underline{T}}\underline{V}^{**\prime} - \frac{\partial\overline{w}^{**}}{\partial\overline{T}}\overline{V}^{**\prime}) + (1-\theta)\frac{\partial\overline{w}^{*}}{\partial\overline{T}}\overline{V}^{*\prime}}{[(1-\theta\underline{\pi})\frac{\partial\underline{w}^{**}}{\partial\underline{T}}\underline{V}^{**\prime} - \theta(1-\underline{\pi})\frac{\partial\overline{w}^{**}}{\partial\overline{T}}\overline{V}^{**\prime}]\frac{\partial\overline{w}^{*}}{\partial\overline{T}}\overline{V}^{*\prime}}$$

As $\theta(1-\underline{\pi}) < (1-\theta\underline{\pi})$, if $\frac{\partial\underline{w}^{**}}{\partial\underline{T}}\underline{V}^{**\prime} > \frac{\partial\overline{w}^{**}}{\partial\overline{T}}\overline{V}^{**\prime}$ then $(1-\underline{\pi})\theta\frac{\partial\overline{w}^{**}}{\partial\overline{T}}\overline{V}^{**\prime} < (1-\theta\underline{\pi})\frac{\partial\underline{w}^{**}}{\partial T}\underline{V}^{**\prime}$ implying $\gamma < 0$ which is not possible. Therefore $\frac{\partial\underline{w}^{**}}{\partial\underline{T}}\underline{V}^{**\prime} < \frac{\partial\overline{w}^{**}}{\partial\overline{T}}\overline{V}^{**\prime}$. In addition, it must be that $(1-\underline{\pi})\theta\frac{\partial\overline{w}^{**}}{\partial\overline{T}}\overline{V}^{**\prime} < (1-\theta\underline{\pi})\frac{\partial\underline{w}^{**}}{\partial\underline{T}}\underline{V}^{**\prime}$ to get $\gamma \geq 0$.

We have $\theta = (\eta+\gamma)\theta\frac{\partial\overline{w}^{**}}{\partial\overline{T}}\overline{V}^{**\prime} - \gamma\overline{V}^{*\prime}\frac{\partial\overline{w}^{*}}{\partial\overline{T}}$ and $\frac{\frac{\partial\underline{w}^{**}}{\partial\underline{T}}\underline{V}^{**\prime}}{\frac{\partial\overline{w}^{**}}{\partial\overline{T}}\overline{V}^{**\prime}} = \frac{\theta(1-\underline{\pi})}{1-\theta\underline{\pi}} - \frac{\theta(\theta-1)}{(1-\theta\underline{\pi})(\theta+\gamma\overline{V}^{*\prime}\frac{\partial\overline{w}^{*}}{\partial\overline{T}})}$ then

$$\frac{\overline{V}^{**\prime}}{\underline{V}^{**\prime}} = \frac{\frac{\partial\underline{w}^{**}}{\partial\underline{T}}}{\frac{\partial\overline{w}^{**}}{\partial\overline{T}}}\left(\frac{\theta(1-\underline{\pi})}{(1-\theta\underline{\pi})} + \frac{\theta(1-\theta)}{(1-\theta\underline{\pi})(\theta+\gamma\overline{V}^{*\prime}\frac{\partial\overline{w}^{*}}{\partial\overline{T}})}\right)^{-1} \geq \frac{\frac{\partial\underline{w}^{**}}{\partial\underline{T}}}{\frac{\partial\overline{w}^{**}}{\partial\overline{T}}} = \frac{\underline{\sigma}_U^{**}}{\overline{\sigma}_U^{**}}\frac{\overline{\sigma}_U^{**}+\overline{\sigma}_V^{**}}{\underline{\sigma}_U^{**}+\underline{\sigma}_V^{**}}$$

In the CARA case,

$$\begin{aligned}\eta+\gamma &= \frac{1-\theta}{(1-\theta\underline{\pi})\frac{\partial\underline{w}^{**}}{\partial\underline{T}}\underline{V}^{**\prime} - \theta(1-\underline{\pi})\frac{\partial\overline{w}^{**}}{\partial\overline{T}}\overline{V}^{**\prime}} \\ \gamma &= \frac{\underline{V}^{**\prime}-\overline{V}^{**\prime}}{\theta(1-\underline{\pi})\overline{V}^{**\prime}-(1-\theta\underline{\pi})\underline{V}^{**\prime}}\frac{\theta(1-\theta\underline{\pi})}{\frac{\partial\overline{w}^{*}}{\partial\overline{T}}\overline{V}^{*\prime}}\end{aligned}$$

That is

$$\eta = \frac{\theta(1-\theta\underline{\pi})(\underline{V}^{**\prime}-\overline{V}^{**\prime}) + (1-\theta)\frac{\partial\overline{w}^{*}}{\partial\overline{T}}\overline{V}^{*\prime}}{[(1-\theta\underline{\pi})\underline{V}^{**\prime}-\theta(1-\underline{\pi})\overline{V}^{**\prime}]\frac{\partial\overline{w}^{*}}{\partial\overline{T}}\overline{V}^{*\prime}}$$