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# On the Informational Superiority of Quantities Over Prices in the Presence of an Externality

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**Abstract** In this study we investigate the convexity of the profit function of a regulated firm with respect to the random shocks in the marginal costs and the demand intercept, and its implications regarding information disclosure when these shocks are revealed to the firm at a future stage. We illustrate that information disclosure is attained when the firm is regulated through the use of a quantity rather than a price instrument. To do so, we argue that increased convexity obtained under complete information is a sufficient condition. As a policy implication, we suggest a new argument which favors the use of quantities over prices. These implications are more pronounced once we allow for multiple firms.

**Keywords** Environmental regulation · Information disclosure · Quantities versus prices

**JEL Classification** F12 · F18 · Q58

## 1 Introduction

A key feature in vertical relations where the upstream agent (e.g., regulator or an input supplier) controls the downstream firm which serves the market is that, usually, the downstream firm possesses superior information. If the upstream agent cannot acquire this information the decision about the mode and the level of regulation is made under uncertainty. One well-known and continuous debate in regulation theory was posed by Weitzman (1974) where the regulator acting under uncertainty needs to decide whether to regulate through prices or quantities. Weitzman's model can be applied to externalities from pollution. Pollution can be

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regulated through an emissions standard (quantity) or an emissions tax (price). Weitzman's rule suggests that the slopes of marginal costs and marginal benefits must be compared.[1]

As Montero (2008) points out, regulators know little about firms' pollution abatement costs. This in turn makes them unable to establish the efficient level of pollution without communicating with the firms. Whenever information acquisition is possible the regulator can decide under complete information and this may lead to welfare gains. Therefore information acquisition should be promoted, especially when it comes at no cost, i.e., in the presence of voluntary agreements. In fact, on the European Environment Agency's website this is explicitly mentioned:[2] "We need information as a prerequisite for environmental improvement. We need an excellent, common, accessible environmental knowledge base as a foundation. The problems can only be solved if we see the big picture beyond the parts. And we need to know what's happening now, not just 10 years ago, and everywhere, not just next door." In China the Ministry of Environmental Protection (MEP) was the first ministry to operationalize general regulations into the Environmental Information Disclosure Decree (EIDD) on May 1, 2008, and it requests that serious industrial polluters disclose environmental information to the public, making the public a more active actor in managing environmental risks (Mol and Guizhen 2011).[3] Apart from voluntary agreements, mandatory information requirements can be placed by the authorities. For instance, in Gujarat, the Gujarat Pollution Control Board enforces command-and-control pollution regulations and monitors approximately 20,000 plants. To obtain relevant information a mixed auditing scheme from third parties is implemented (see Duflo et al. 2013).

In this paper we consider the effect of voluntary information disclosure agreements on the choice between prices and quantities when the regulator is uncertain about the future value of the marginal cost and/or the demand intercept. We show in this framework that the regulator will in general prefer quantities to prices. For this to be true when the agreement is set both the firm and the regulator must be uncertain regarding the exact value of the shock(s). This is consistent with the way Weitzman (1974, p.480) perceives uncertainty: "Even the engineers most closely associated with production would be unable to say beforehand precisely what is the cheapest way of generating various hypothetical output levels. How much murkier still must be the centre's ex ante conception of costs, especially in a fast moving world where knowledge of particular circumstances of time and place may be required…." Based on the fact that firms are expected to acquire information at a future stage such agreements should be feasible.

In particular, when the regulator implements quantities, regulation adjusts to the incoming information such that expected profits of the firm increase inducing the firm to agree on disclosing future information. On the contrary, when prices are implemented regulation responds to the shock(s) differently. This in turn implies that disclosing future information reduces expected profits of the firm. Put differently, the implementation of a quantity

[1] The basic results present in Weitzman (1974) have been replicated and extended further in important studies, among others, by Adar and Griffin (1976), Fishelson (1976), Stavins (1996), Montero (2002), Quirion (2004) and Heuson (2010). Extensions toward a dynamic framework of the debate are presented by Karp and Zhang (2012) and Angelopoulos and Economides (2013).

[2] Details can be found at: http://www.eea.europa.eu/about-us/what/information-sharing-1/information-sharing.

[3] Voluntary information sharing agreements have been observed in many types of vertical relations. Indeed, as Creane (2008) claims, there is ample evidence that firms share information with their worker unions. Moreover, such agreements are common between governments and firms regarding export trade policies. For instance, the U.S. Export-Import Bank (2005) requires both demand and cost information from any applicant.

instrument enhances risk loving-behavior of the firm. These findings are indeed magnified once we allow for many firms.

The result regarding information disclosure is based on the fact that information is verifiable by the regulator. If this is not true, once the firm learns the true state of the shock has an incentive to misreport the values of the shocks when these result in tighter regulation. This, in turn, affects the incentive of the regulator to participate in an eventual agreement. Introducing assumptions taken from the relevant literature regarding the functional forms, we show that when quantities are implemented the regulator is likely to participate into an agreement. In this case regulation is sub-optimal when the firm misreports and it is not detected by the regulator. Nonetheless, the benefits of the regulator from learning the true value of the shock with a positive (relatively high) probability are still in place. Moreover, we argue that limited verifiability is less of an issue when quantity regulation is complemented by a fine-penalty once a firm is detected to misreport.

*Related Literature*: The result of information sharing per se is not a novelty of our findings, since this has been well presented, in different setups, by Li (2002), Creane (2007, 2008), Creane and Miyagiwa (2008), and Creane and Davidson (2008).[4] There are two types of novelties in the current study. The first is in terms of results, while the second is an analytical one. Regarding the results, we illustrate that the mode of regulation is crucial for information acquisition. When the regulator selects a quantity instrument to control pollution under uncertainty regarding the demand intercept and the marginal abatement cost, a firm willingly accepts revealing its future information. In contrast, when the regulator chooses a price instrument the firm does not agree to disclose information. Hence, the regulator may select the appropriate level of regulation under *complete* information when a quantity constraint is implemented. This provides the regulator with an advantage compared to the case where a price instrument is implemented. In this case quantities always lead to superior expected welfare outcomes compared to prices. Following this argument, there is no need for a sophisticated mechanism to acquire information (e.g., Kwerel 1977; Spulber 1988; Rob 1989; Lewis 1996). *Ex ante* contracting when quantities are implemented leads to the desired outcome (first-best) without the use of a non-linear scheme. Regarding the analytical novelty, we explore the shape of the profit function with respect to the two random shocks over the demand intercept and the marginal abatement cost, while the assumptions requested are minimal.

It is important to note that there are well-known studies that provide simple mechanisms to implement the efficient allocations for economic environments involving externalities under incomplete information. One stream of the literature from Varian (1994) and Duggan and Roberts (2002) shows that efficient allocations can be achieved as subgame perfect Nash equilibria or even as Nash equilibria respectively in a budget neutral way. However, these studies allow the firms to monitor each other. The second stream of the literature, represented by Unold and Requate (2001), Krysiak (2008), Montero (2008), and Yates (2012) suggest that efficiency may be obtained by a proper selection of the permit supply function.[5] The advantage of our results is that efficiency can be achieved once incomplete information is resolved by fixing quantities at the level where the optimal condition is met.

Finally, there is a parallel literature on the dynamic implications of the mode of regulation on learning (e.g., Moledina et al. 2003; Costello and Karp 2004). Moledina et al. (2003) recognize that when pollution emitted is observable the firms may act strategically to affect

[4] Note that these papers deal with vertical information sharing. In contrast, horizontal information sharing has been widely explored. Raith (1996) provides a general overview of the results.

[5] Non-constant regulation was introduced by Roberts and Spence (1976) and Weitzman (1978).

future regulation. Taxes induce over-abatement so that future regulation is relaxed and are in general superior to permits from a welfare standpoint when the permit price is set by the efficient firm. Our model shares similarities with this study in that future regulatory adjustment follows the same pattern given the mode of regulation, as well as that the ranking of the policy instruments does not depend on the slopes of the marginal abatement cost and of the marginal damage from pollution respectively. In Moledina et al. (2003) the ranking of the policy instruments depends on which policy is indeed less distortive, whereas our superiority of quantities over prices is based on the fact that when the first are implemented the regulator acts under complete information. This also contradicts the findings of Costello and Karp (2004) where the reverse ranking is obtained since taxes induce immediate learning due to observability of emissions. Such dynamic considerations are however orthogonal to the issues we address and therefore our model abstracts from those ones.

## 2 The Model

### 2.1 Structure

We consider a model with a single active firm in the economy producing output, $x$. The consumer's utility from $x$ is $v(x) = U(x) + \theta x$, where $U(\cdot)$ stands for the deterministic part of the utility and $\theta$ is a zero mean random variable. We assume that the consumers' marginal utility of the good, or alternatively the demand, is positive but decreasing, that is, $v_x(\cdot) > 0$ and $v_{xx}(\cdot) < 0$.[6] If $v_{xxx}(\cdot) \neq 0$ then the demand is non-linear. In particular, when $v_{xxx}(\cdot) < 0$ ($> 0$) the demand is concave (convex). In addition to that, output $x$ is associated with an externality (e.g., pollution), $z$, which adversely affects consumers through a damage function $d(z)$, and it is increasing and convex, i.e., $d_z(\cdot) > 0$ and $d_{zz}(\cdot) \geqslant 0$. The firm faces two options in order to deal with the externality. First, to reduce output, and second, to use a costly abatement technology and thus the net level of the externality equals production minus abatement carried out by the firm,

$$z = x - a. \tag{1}$$

The abatement cost function is denoted by $c(a) = C(a) + au$, where $C(\cdot)$ stands for the deterministic part of the costs and $u$ represents a random additive shock to the marginal costs of abatement and follows a distribution with zero mean. For simplicity and without loss of generality, we neglect production costs and we assume that the firm incurs only the costs of abatement, which are increasing and convex, i.e., $c_a(\cdot) > 0$ and $c_{aa}(\cdot) > 0$.

Given these, it follows that the profit function of the firm depends on the policy instrument chosen by the regulator and it is given by the following expression:

$$\pi = v_x(\cdot)x - c(\cdot) - tz \cdot \mathbf{1}_{\{t>0\}}, \tag{2}$$

where $tz$ are the tax payments due to the externality and $1_{\{t>0\}}$ the indicator function, denoting whether the tax $t$ is implemented ($t > 0$) or not ($t = 0$). The choice variables of the firms are output and the abatement level. We examine two different modes of regulation. First, we assume that the regulator can use a standard, i.e., a maximum allowed level of the externality by the firm, which translates to a quantity constraint. The alternative policy instrument available to the regulator is a tax, $t$, per unit of the externality which is considered to be a price instrument. The regulator in both regimes chooses the optimal level of regulation by maximizing welfare which is given by:

[6] The subscripts throughout the paper will denote the partial derivatives of a function with respect to the indicated variable or parameter.

$$w = v(\cdot) - c(\cdot) - d(\cdot). \tag{3}$$

## 2.2 Timing

The timing of the model is shown in Fig. 1.[7]

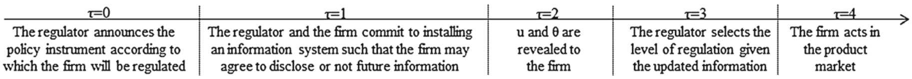


**Fig. 1** Timing of events

In the case where the firm does not agree to disclose information the regulator must decide on the optimal level of regulation without observing the actual values of the stochastic parameters. This resembles Weitzman's (1974) paper after introducing an explicit structure in the economy and a second stochastic term regarding the demand. However, if the firm agrees upon future information disclosure and this agreement can be enforced then the regulator may decide under complete information.[8] If this is the case then the story behind Weitzman is irrelevant since the participants, the regulator and the firm, will have an incentive to resolve the incomplete information problem endogenously.

For this to hold, information must be verifiable by the regulator. Clearly, this is an idealized starting point, but presents a clear benchmark and allows us to isolate the effects we are interested in. In reality we shall expect that the regulator learns only coarse information, e.g., a new updated distribution with a different mean which converges to the true value. In this case the regulator still benefits from information disclosure. However, in Sect. 5 we discuss the possibility of misreporting and its effect over signing a contract or not. Moreover, limited verifiability can be resolved as soon as a fine-penalty is imposed to the firm for misreporting (see Baron and Besanko 1984).

An agreement should involve a kind of inspection by the regulator to learn information. This can be achieved if, for example, the regulator imposes a representative to serve on the firm's board of directors or by allowing a third party to audit the firm's books. For instance, since 1996 (see Gujarat High Court 1996), Gujarat, one of India's fastest growing industrial states, has had a third party audit system for plants with high pollution potential. According to this mandate, auditors annually submit plant pollution readings and report to the regulator the production process including measures taken for pollution control. As discussed by Duflo et al. (2013) the status quo audit reporting was corrupted. Yet, they also argue that a treatment, which included random auditor assignments, fixed payments from a central pool, back-checks, and incentive payments, improved significantly the accuracy of reports. In a different problem studied by Olken (2007), regarding corruption in public projects, it is shown that traditional top-down monitoring plays an important role in reducing corruption.

## 3 Information Disclosure Decision

In order to determine whether the regulator and the firm achieve an agreement regarding information disclosure or not we need to split the analysis given the two different modes of regulation. We start our analysis by solving backwards for the case where the regulator selects

[7] Though in a completely different setup, the timing resembles the one introduced by Courty and Li (2000), where the agents first learn their distributions and then at a future stage they acquire the actual information.

[8] Note that our model is restricted to a single period game. Thus learning occurs only when the firm communicates its private information to the regulator. In a dynamic framework, learning may also occur in the absence of an agreement by observing past emissions and thus regulation adjusts in the next period (see Costello and Karp 2004).

a standard to deal with the externality. Here on, we will take for granted that the regulator is willing to receive information and therefore the agreement should be fulfilled once the firm agrees to disclose future information. The reader can perceive this as a revealed preferences argument. Since, this is a one-sided asymmetric information problem the current model can support various modifications as everything is determined downstream.

## 3.1 Standard

### *3.1.1 Complete Information*

Initially, we assume that the regulator and the firm agree to share information. Hence, the problem is reduced to a simple complete information game. We solve the problem backwards. When a standard is implemented, the firm has a unique control variable (production), since abatement must be chosen such that Eq. (1) is satisfied. Bearing this in mind, the first order condition from profit maximization is,

$$
\begin{aligned}
&\pi_x = 0 \\
&s.t. a = x - z \\
&\qquad \Longleftrightarrow \; v_x + x v_{xx} - c_x = 0.
\end{aligned}
\tag{4}
$$

The second order condition is $\pi_{xx} = 2v_{xx}(\cdot) + x v_{xxx}(\cdot) - c_{xx}(\cdot) < 0$. Note that in order for this condition to be satisfied the demand should not be too convex. Given this and after differentiating (4) with respect to $z$, $u$ and $\theta$ respectively we obtain the following:[9]

$$
x_z = -\frac{c_{xx}}{\pi_{xx}} > 0 \in (0, 1) \;\text{ and }\; x_u = -x_\theta = \frac{1}{\pi_{xx}} < 0. \tag{5}
$$

From (5) we observe that when regulation is relaxed the firm increases its output. If a shock which increases the intercept of the marginal cost of abatement or decreases the demand intercept (negative shock) occurs then output is reduced and vice-versa.

Given the firm's output, the regulator selects the optimal standard by maximizing welfare:

$$
w_z = v_x x_z - c_x x_z - c_z - d_z = 0. \tag{6}
$$

The second order condition is $w_{zz} = -\left[(x_z - 1)^2 c_{xx} + d_{zz} - x_z^2 v_{xx} + (c_x - v_x) x_{zz}\right] < 0$. From Eq. (6) we observe that the regulator must weigh, on the one hand, the incentive to relax the standard in order to reduce the abatement costs and so increase the consumers' surplus through the higher quantity produced, and on the other hand, the incentive to tighten regulation to mitigate the damage caused from the externality. Any reduction in output below the optimal unregulated level indirectly imposes a cost on the firm and must be considered. Moving back to Eq. (6) we observe through (4) and (5) that as long as the firm is not a price taker, which would imply $(v_x - c_x) x_z = 0$, the optimal level of the standard is shifted upwards compared to the first-best.

For our analysis it is crucial to know how the optimal level of regulation changes when a random shock occurs. The following remark presents these changes:[10]

*Remark 1* (a) $z_u^* > 0$ when $x_{zu} \simeq 0$, and (b) $z_\theta^* > 0$ when $x_{z\theta} \simeq 0$.

In general the sign of $z_u^*$ cannot be inferred directly. It describes how the optimal standard changes when a shock occurs. When positive the optimal standard increases as a response to

[9] We employ $-c_{xz} = -c_{zx} = c_{xx} = c_{zz}$ and $c_{xu} = 1$.

[10] All proofs are relegated to the Appendix.

the higher abatement cost. Two effects are crucial to determine the overall sign. A primary positive one which follows from the fact that when abatement costs are higher regulation is laxer, and a secondary one which has an ambiguous sign. The latter is captured by $x_{zu}$ which describes how the response of output on regulation is affected by the shock. Standard intuition implies that the secondary effect should be rather small. For instance, when we assume quadratic costs and damage functions as in Weitzman (1974) and a linear demand as in Heuson (2010) the secondary effect vanishes. Hence, for small deviations from this benchmark, the sign should remain positive. The analysis regarding Remark 1b follows similarly.

### 3.1.2 Incomplete Information

Now, we turn to the case where an agreement upon information sharing is not achieved. The firm's decision problem remains unaffected and it is again described by Eq. (4). However, for the regulator to select the optimal level of the standard, the expected welfare function is maximized. Since, $u$ and $\theta$ are additive to (4) it follows that the partial effects observed by the regulator are the following:

$$E\left[x_z\right] = E\left[-\frac{c_{xx}}{\pi_{xx}}\right] \text{ and } E\left[x_u\right] = E\left[x_\theta\right] = 0, \tag{7}$$

where the operator $E$ stands for the expected value. From (7) we observe that when the regulator maximizes the expected welfare the effects of the random shocks over output decisions are not considered. The decision on the level of regulation is given by the following expected welfare maximization with respect to $z$:

$$E\left[w_z\right] = 0, \tag{8}$$

where the second order condition is $E\left[w_{zz}\right] < 0$. The implications of the level of regulation are similar to those following Eq. (6).

Given these, the following remark presents how the optimal level of regulation changes for a given random shock under incomplete information:

*Remark 2* (a) $z_u^{**} = 0$, and (b) $z_\theta^{**} = 0$.

Remark 2 is straightforward and simply states that when an agreement is not reached then regulation cannot adjust to the exogenous shock(s).

### 3.1.3 Conditions for Information Disclosure

For the firm to decide whether to agree or not, the expected profits for the two scenarios must be computed and then compared. Since, however, we have not introduced any specific functional forms thus far we cannot calculate them explicitly. Yet, we can compare them by exploring the convexity of the profit function with respect to the stochastic terms in the two scenarios, i.e., complete and incomplete information. We first define $z_{uu}^*$ and $z_{\theta\theta}^*$ as the indirect effects.[11] Then, the following proposition summarizes the comparison of the degrees of convexities of profits with respect to each stochastic term and then derives a ranking of the corresponding values of the expected profits:

[11] Note, that in the papers that introduce specific quadratic functions, e.g., Weitzman (1974) and Heuson (2010), the indirect effect is absent.

**Proposition 1** *Given that the indirect effects are relatively small then: (a) $z_u^* > 0 \Rightarrow \pi_{uu} > \pi_{uu}^{un}$ and information disclosure occurs. (b) $z_\theta^* > 0 \Rightarrow \pi_{\theta\theta} > \pi_{\theta\theta}^{un}$ and information disclosure occurs.*

From Proposition 1 we observe that complete information may translate to a more convex profit function compared to the incomplete information case. Establishing convexity of the profit function with respect to the shock implies that the firm is willing *ex ante* to disclose information. This is independent on the type of the shock and thus the rationale is the same for both cases.

There are two main determinants of convexity, a direct and an indirect one. In the case of a shock over the marginal cost of abatement, the direct effect is determined after taking into account several sub-effects. The prevailing effect is that the adjustment of regulation in the shock, $z_u^*$, along with the shock per se, $u$, tends to increase convexity. Yet, the adjustment of regulation tends to decrease convexity due to the fact that the profit function is concave both with respect to output and abatement. Nonetheless, the overall direct effect is always positive.

The indirect effect, restricted in Proposition 1 to be relatively small for illustrative purposes, captures the change in convexity attributed to the rate of the regulatory adjustment and can be either positive or negative depending on the curvatures of our functions. From the corresponding proof in the Appendix it follows that if regulation adjusts at an increasing rate ($z_{uu}^* > 0$) convexity of profits increases. In the opposite case, the indirect effect is negative which in turn tends to decrease convexity. Then, the indirect effect should not outweigh the direct positive effect ($\simeq 0$). Especially, for small shocks this should always be the case.

Regarding Proposition 1b the analysis is similar. Here, the prevailing sub-effect is positive. That is, the adjustment of regulation on $\theta$ along with the shock per se outweighs the negative sub-effects present due to the concavity of the profit function with respect to output and abatement. Similarly to the previous case, the indirect effect can increase convexity when positive and the reverse. Again for any well-known example the indirect effect is inexistent.

Convexity per se is sufficient to justify information disclosure as it leads to higher expected profits in the case of complete information compared to the corresponding ones in the incomplete information case. To understand the mechanics we introduce Fig. 2. Part (a) of the diagram represents the profit functions under complete information (red/flatter) and incomplete information (blue/steeper) as a function of $u$. The higher $u$ implies higher marginal abatement costs and thus lower profits. The difference in the degree of convexity implies that they are decreasing at different rates. At the point where the actual value of the shock coincides with the expected value ($u = 0$) profits are equal. In case of negative news, $u > 0$, under complete information, regulation is relaxed ($z_u^* > 0$) which reduces profits at a lower rate compared to the corresponding ones under incomplete information. As the actual value of the shock increases, the difference in profits increases as well. In case of good news, $u < 0$, then profits under incomplete information are higher than the profits under complete information since in the latter case the regulator tightens regulation accordingly. The difference, however, grows at a decreasing rate for more negative values of the shock. Therefore, the expected benefits from information disclosure should outweigh the expected losses and therefore information disclosure is optimal. Put differently, the regulator, in case of negative news provides the firm with an insurance through laxer regulation, while for positive news the firm must suffer the extra regulation corresponding to the optimal regulation level.

The analysis regarding the part (b) of Fig. 2 follows similarly. Here, profits are drawn as a function of the shock in the demand intercept. Again, profits across the two states of information coincide when $\theta = 0$. In case of good news, $\theta > 0$, the regulator relaxes the standard, increasing further the profits under complete information. Due to convexity

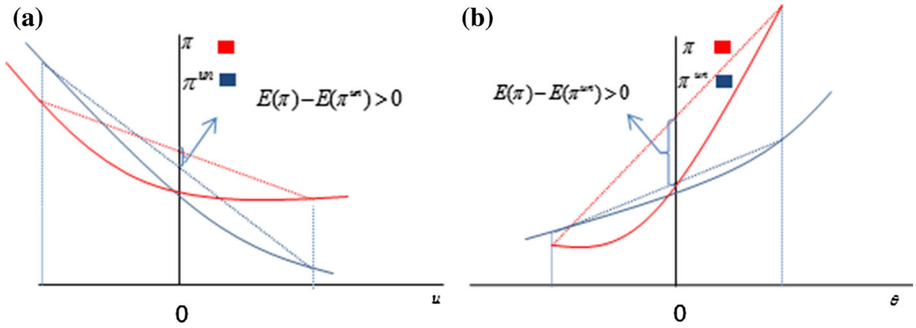


**Fig. 2** Expected profits under both informational structures as a function of the stochastic terms (Standard). **a** Abatement cost uncertainty, **b** Demand uncertainty

for $\theta > 0$ the difference in profits increase at an increasing rate. For $\theta < 0$ profits under incomplete information are higher, yet the difference increases at a decreasing rate as $\theta$ takes larger negative values. Again, expected profits are higher under complete compared to the ones under incomplete information.

An important implication drawn from the results above is that information disclosure does not depend on the level of uncertainty, i.e., the variance. It is also of some interest to focus on the components affected by the stochastic terms. A detailed examination of the partial effects presented in the model suggests that, under both modes of uncertainty, the slopes of the marginal abatement costs and marginal damage are crucial for the expected benefits and losses from disclosing. Hence, if the slope of the marginal abatement costs is rather steep the negative effect in expected profits is strengthened. When the slope of the marginal damage is rather steep regulation is less responsive in the shocks and thus expected profits do not differ significantly. In the extreme case where the marginal damage is infinitely elastic then regulation is fixed regardless of the shock, which implies that the firm is indifferent between disclosing information or not.

## 3.2 Tax

### *3.2.1 Complete Information*

In contrast to the previous case we now assume that the regulator implements a tax to control the externality. Now the firm has two control variables available, output and abatement. Solving backwards we derive the first order conditions for the firm:

$$\pi_x = 0 \iff v_x + x v_{xx} - t = 0 \tag{9}$$
$$\pi_a = 0 \iff c_a = t. \tag{10}$$

The second order conditions are satisfied since $\pi_{xx} = 2v_{xx}(\cdot) + x v_{xxx}(\cdot) < 0, \pi_{aa} = -c_{aa} < 0$ and $\pi_{xa} = 0$. The first among these conditions is satisfied when the demand is not too convex. Equation (10) states that the marginal cost of abatement equals the tax. Given this and after differentiating (9) and (10) with respect to $t$, $u$ and $\theta$ respectively we obtain the following:

$$x_t = \frac{1}{\pi_{xx}} < 0, a_t = -\frac{1}{\pi_{aa}} > 0, z_t = x_t - a_t < 0, x_u = a_\theta = 0,$$
$$x_\theta = -x_t > 0 \text{ and } a_u = -a_t < 0. \tag{11}$$

From (11) we observe that when regulation is relaxed the firm increases its output while abatement is reduced and vice-versa. A shock which increases the intercept of the marginal cost of abatement has no effect on output and similarly any shock over the demand intercept does not affect the abatement decisions. Contrary to these, a shock over the demand affects output positively, while a shock in the marginal abatement costs intercept adversely affects the abatement level.

Given the firm's output and abatement decisions, the regulator selects the optimal tax by maximizing welfare:

$$w_t = v_x x_t - c_a a_t - d_z z_t = 0. \tag{12}$$

The second order condition is $w_{tt} = v_{xx}x_t^2 + v_x x_{tt} - c_a a_{tt} - c_{aa}a_t^2 - d_{zz}z_t^2 - d_z z_{tt} < 0$. Akin to the case of a standard, from Eq. (12) we observe that when maximizing welfare through the use of a tax the regulator must weigh the incentive to relax the tax to raise production and increase consumers' surplus, and the incentive to strengthen regulation such that the damage from the externality is controlled.

As in the case of standards, regulation should be set such that the tax is below the first-best level. This can be observed once we manipulate the terms in Eqs. (9) and (12) such that the first order condition transforms to $v_{xx}x_t = (t - d_z)\, z_t$. Since the left hand side is positive so is the right hand side, i.e., $t < d_z$.

The following remark shows how the optimal tax changes with respect to the two shocks:

*Remark 3* (a) $t_u^* > 0$ when $a_{tt} \simeq 0$, and (b) $t_\theta^* > 0$ when $x_{tt} \simeq 0$.

From Remark 3a we observe that as long as the secondary effect captured by $a_{tt}$ is relatively small compared to the primary effect, the sign of $t_u^*$ is positive. When $u > 0$, the primary effect implies that the regulator increases the tax to equalize the marginal damage to total marginal abatement costs. The secondary effect captured by $a_{tt} = -a_{tu}$ describes how the response of abatement on regulation is affected by the shock. In the linear specification the secondary effect is equal to zero, and therefore we shall expect this to hold for small departures from this case. As in the case of standards the curvature of the abatement cost function determines the sign of the secondary effect, yet, the primary effect should dominate. That is, a negative shock in abatement costs induces the regulator to tighten regulation and vice-versa.

The analysis for Remark 3b follows similarly though the positive sign of the primary effect is harder to unmask. Indeed the primary effect is positive as long as pollution internalization drives the regulator to set a positive tax. That is the slope of the marginal damage is relatively high (see "Appendix"). This can be clearly observed under a linear specification. Then the effects present due to a possible curvature of the demand function disappear. A positive sign implies that a positive shock in demand should be followed by a higher tax while lower future demand should lead to laxer regulation.

### 3.3 Incomplete Information

The next step is to examine the case where an agreement upon information disclosure is not achieved. Therefore, when a shock occurs in the economy it is not observed by the regulator, who maximizes his expected welfare with respect to the tax. The firm's decision problem remains unaffected and it is again described by Eqs. (9) and (10 ). However, when the regulator selects a tax the expected welfare function is maximized. Since, $u$ and $\theta$ are additive to the first order conditions of the firm, (9) and (10), it follows that the partial effects that the regulator observes are the following:

$$E\left[x_t\right] = E\left[\frac{1}{\pi_{xx}}\right] < 0,\ E\left[a_t\right] = E\left[-\frac{1}{\pi_{aa}}\right] > 0 \text{ and } E\left[x_u\right] = E\left[x_\theta\right] = E\left[a_u\right] = E\left[a_\theta\right] = 0. \tag{13}$$

where the operator $E$ stands for the expected value. From (13) we observe that when the regulator maximizes the expected welfare, the effect of the random shocks over output and abatement are not considered. The decision about the tax is given by the following maximization of the expected welfare with respect to $t$:

$$E\left[w_t\right] = 0, \tag{14}$$

where the second order condition is $E\left[w_{tt}\right] < 0$. The implications of the level of regulation are similar to those following Eq. (12).

Given these, the following remark shows how the optimal level of regulation changes when a random shock occurs for the case of incomplete information:

*Remark 4* (a) $t_u^{**} = 0$, and (b) $t_\theta^{**} = 0$.

Remark 4 simply states that when an agreement is not reached then regulation does not adjust to the exogenous shock.

### *3.3.1 Conditions for Information Disclosure*

Similar to the case of the standard it is sufficient to compare the shape of the profit function with respect to $u$ and $\theta$ across the two different states in order to determine whether each participant would like to participate in a potential agreement or not. Again we define $t_{uu}^*$ and $t_{\theta\theta}^*$ as the indirect effects. Hence, it follows:

**Proposition 2** *Given that the indirect effects are relatively small then: (a) $t_u^* > 0 \Rightarrow \pi_{uu} < \pi_{uu}^{un}$, and information disclosure does not occur. (b) $t_\theta^* > 0 \Rightarrow \pi_{\theta\theta} < \pi_{\theta\theta}^{un}$ and information disclosure does not occur.*

The results move toward the opposite direction of Proposition 1. Again there is a direct and an indirect effect. The direct effect, suggests that under complete information convexity is reduced because of the policy scheme. When the indirect effect is relatively small then the net outcome is clear and information sharing does not occur in any case. In general, the indirect effect can be either positive or negative. In the first case, i.e., regulation adjusts at an increasing rate, disclosing information reduces convexity even further, decreasing the *ex ante* incentives to share information. When the indirect effect is negative, provided that it is lower than the direct one in absolute terms, it mitigates the direct one.

The introduction of Fig. 3 serves to ease the analysis. The red curves represent the profits under complete information, which are realized when the firm reveals information to the regulator, and the blue curves again represent the incomplete information case, which translates to the scenario where the regulator remains uninformed. The signs of $t_u^*$ and $t_\theta^*$ drive the results. Focusing on part (a) related to the stochastic term $u$, we observe that for $u = 0$ profits are the same across the two states. For $u > 0$ profits under incomplete are higher than profits under complete information as $t_u^* > 0$. Therefore, announcing the actual value to the regulator leads to higher taxation, which harms profits. Due to the fact that the profit function under incomplete information is now more convex compared to the corresponding one under complete, the difference rises at an increasing rate for larger values of $u$. For negative

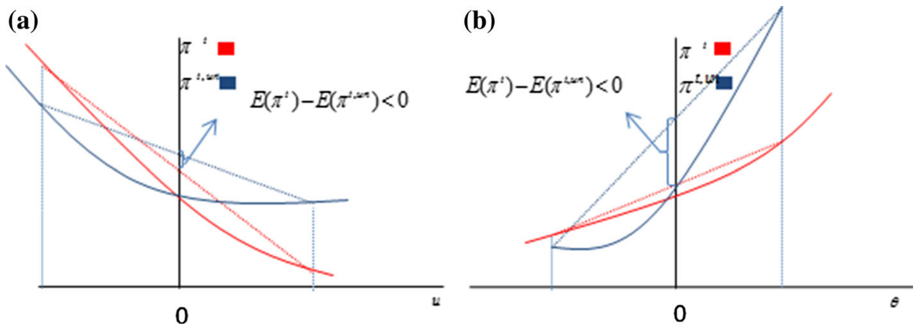


**Fig. 3** Expected profits under both informational structures as a function of the stochastic terms (Tax). **a** Abatement cost uncertainty **b** Demand uncertainty

values of $u$, profits under complete are now higher than the ones under incomplete information and, given the difference in convexities, this difference increases at a decreasing rate. Hence, profits from an *ex ante* perspective are higher under incomplete rather than complete information.

A similar rationale is followed for the graph on part (b) regarding the shock over the demand intercept. When $t_\theta^* > 0$, then for good news ($\theta > 0$) the regulator punishes the firm for revealing information. The difference in profits increases at an increasing rate. Contrary to that, when the firm announces the bad news ($\theta < 0$) the regulator relaxes regulation, which in turn raises profits. However, this benefit is not sufficient to offset the negative incentive that the firm faces on disclosing information.

When a tax is implemented the level of uncertainty does not affect the decision regarding information disclosure. In addition to that, it is important to note that the slopes of the demand, marginal abatement costs and marginal damage should affect the results and their magnitude since information disclosure increases the volatility of the variables that profits depend on.

The results regarding information sharing are exactly the opposite in the case of standards and taxes. In the case of standards, information disclosure occurs because regulation responds in a way so that for a positive shock the firm benefits at an increasing rate, while when the shock is negative the firm is punished at a decreasing rate. When an emission tax is in place, then for a positive shock, information disclosure harms the firm's profitability at an increasing rate, whereas for a negative shock, revealing information increases the firm's profitability, yet at a decreasing rate.

## 4 Policy Instrument Choice Game

Given the results thus far we have already obtained an important difference between the cases where the regulator implements a standard instead of a tax. When the first is implemented we have determined that incomplete information is endogenously resolved for any of the two shocks introduced. This difference is crucial in $\tau = 0$ where the regulator selects the policy instrument to be used. The possibility to set an agreement between the firms and the regulator regarding disclosure of information alters the answer in the original debate posed by Weitzman regarding the ordering of prices vs quantities. Here, we address a similar question as in Weitzman regarding the optimal mode of regulation. Whereas Weitzman's analysis takes place in a second best environment, here, when quantities are introduced the losses attributed to uncertainty vanish as the latter is endogenously resolved. Despite that our model differs from Weitzman's also on the market structure, i.e., here the firms are introduced explicitly in an imperfectly competitive setup, we argue that the key feature is to determine under which regulatory scheme complete information is achieved. Indeed, it can be shown that information disclosure when standards are implemented also occurs if we adjust our assumptions regarding competition to Weitzman. As incomplete information is resolved, the expected welfare losses present in our, as well as in Weitzman's model, due to uncertainty disappear and the comparison of the relative slopes of the marginal abatement cost and marginal damage turns to be irrelevant. In this respect quantities are always superior to prices. The regulator equalizes the marginal damage to the actual total marginal abatement costs. This result is summarized in the following proposition:

**Proposition 3** *When $z_u^* > 0$, $z_\theta^* > 0$ and the indirect effects are relatively small, the implementation of a quantity instrument is always superior to a price one.*

The intuition of this result is straightforward. Since incomplete information is resolved when a quantity instrument is implemented, its use is superior to the price instrument where incomplete information persists. In fact, the comparison of expected welfare levels when a standard is imposed relative to the case where a tax is in place coincides with the difference of expected welfare levels when a tax is used between the cases of complete versus incomplete information. The use of quantities provides the regulator with a flexibility which increases firm's expected profits as the profit function turns more convex. Contrary to that, when a price is implemented higher flexibility is not desired by the firm. The two policy schemes alter the attitude of the firm towards risk. If the firm decides to disclose information then quantity regulation makes the firm more risk-loving, while price regulation leads to the opposite behavior. Put differently, under complete information and quantity regulation a shock is more pronounced because the standard adjusts towards the direction of the shock. Under price regulation when information is disclosed the tax responds to the same direction of the shock, which mitigates the effect of the shock over profits.

Returning to the original Weitzman debate, here, we argue that quantities are superior to prices as long as the indirect effects do not offset the direct ones. In particular, if the regulator does not adjust regulation at a decreasing rate so that the direct effects which translate to a positive adjustment to the shock(s) are reversed, then a superiority of quantities over prices is always sustained. The argument suggested by Heuson (2010) regarding the bias in favor of taxes as they reduce miscalculations here is irrelevant because when standards are implemented there are no miscalculations. While Weitzman suggests that the slopes of the marginal abatement and damage functions must be compared, here this is not the case. The slopes of these functions do not affect the ranking of the policy instruments, but only the magnitude of the difference of the expected values.[12] It is important to note, that this superiority is an informational superiority in terms of *ex ante* incentives of disclosing information. The traditional benefits of price regulation, *inter alia*, efficiency, in a more general framework are still present.

## 5 Extensions

The interested reader may wonder about the robustness of the results in various directions. Two natural candidates that deserve further attention are the introduction of multiple firms and

[12] In a completely different setup which is based on learning information over time Moledina et al. (2003) derive a similar finding where the ranking of the policy instruments depends on who, low or high cost firm, sets the emissions price.

the (limited) verifiability of information. To keep things simple we abstract from the indirect effects and introduce a linear specification of the model following the relevant literature (e.g., Weitzman 1974; Heuson 2010). Clearly, this can be viewed as a benchmark which allows us to highlight the interesting effects and keep the analysis simple. Additionally, here on our analysis will focus only the shock regarding the abatement cost function. In the multiple firms case it is uninteresting to consider the information sharing issue regarding the shock over the demand since this is a common shock; thus extracting information is relatively easy in the context of yardstick competition (Varian 1994). Regarding the verifiability case we do so for brevity as no additional insights are gained.

### 5.1 Multiple Firms

We consider a model with $n$ active firms. We denote the output of a typical firm $i$, $x_{\{i\}}$, and normalize production costs to zero, while each firm faces an inverse demand function $p = A - b\sum_{i=1}^{n} x_{\{i\}}$. The abatement cost function of a typical firm $i$ for which the shock occurs, is assumed to be convex of the form $c(a_{\{i\}}) = \frac{1}{2}ga_{\{i\}}^2 + a_{\{i\}}u$, where $g > 0$ and $u$ is the value of the shock of the individual firm and follows again a distribution with zero mean. The damage from pollution is also convex, $d = \frac{1}{2}k\left(\sum_{i=1}^{n} z_{\{i\}}\right)^2$, where $k > 0$.

*Standards*

First, we compute the outcome under complete information. To abstract from any biases with respect to the case of taxes introduced later on we do not assume that the standard is tailored to each firm. We assume that the regulator sets the same standard to each firm.[13] An additional dimension is now present which can be viewed as learning. This is the case when the agreement between the firm and the regulator allows the last one to inform the remaining firms. Given this we discriminate between these two cases. As the timing of the game remains unchanged with respect to the main part of the paper we solve backwards and determine the Cournot outcome in the product market. Therefore $\tau = 4$ equilibrium outputs are as follows:

$$\left\{\begin{array}{l} x_{\{i\}} = x_{\{u=0\}} - \frac{u}{2b+g} \text{ and } x_{\{j\neq i\}} = x_{\{u=0\}} \\ x_{\{i\}}^{l} = x_{\{u=0\}} - \frac{(g+bn)u}{(b+g)[(1+n)b+g]} \text{ and } x_{\{j\neq i\}}^{l} = x_{\{u=0\}} + \frac{bu}{(b+g)[(1+n)b+g]} \end{array}\right\}, \tag{15}$$

where $x_{\{u=0\}} \equiv \frac{A+gz}{(1+n)b+g}$ is the output of the typical firm when there is no shock and the superscript $l$ stands for learning. From the two sets of outputs in (15) we observe that without learning the output of the other firms remains unaffected. In the case that firm $i$ decides to inform the rival firms then their output depends positively on the shock. The underlying reason is that when $u$ is positive firm $i$ reduces output and thus the best response of the rival firms is to increase their output. It follows directly that $\tau = 4$ equilibrium outputs under uncertainty coincide with the set of Eqs. in (15 ) without learning.

Solving backwards at $\tau = 3$ the regulator determines the optimal standard given the information received. It follows:

*Remark 5* (a) $z_u^* > 0$, and (b) $z_u^{l*} > 0$.

Remark 5 suggests that for the linear specification the result remains unaffected. The intuition is identical to the one introduced previously. When the shock is positive implying

[13] In case that the standard can be tailored to each individual firm then our results are even stronger.

higher marginal abatement costs the regulator has an incentive to raise the standard and vice-versa. Remark 5b suggests that the same holds true for the case where the rival firms learn the value of the shock through the regulator. When the regulator remains uninformed regulation does not adjust accordingly, i.e., $z_u^{**}, z_u^{l**} = 0$.

The following proposition introduces the additional effects over convexity of profits in the presence of many firms:

**Proposition 4** *Given the linear specification, the introduction of n firms increases the convexity of profits with respect to u in both cases.*

Irrespective of learning, the introduction of multiple firms strengthens the results obtained in the single firm case. A positive shock results to laxer regulation for everyone, which implies that the rival firms increase production. Given that the profits of firm $i$ depend negatively on the aggregate output of the rivals the overall sign turns negative. This, combined with the fact that the output of firm $i$ is negatively related to the shock, implies higher convexity. On top of the direct effects discussed in the main part, an additional channel is created through the output of the rival firms. In the case of learning this channel is more pronounced because the output of the rivals is more responsive.

*Taxes*

The tax cannot be tailored to each firm and therefore is uniform. The $\tau = 4$ equilibrium outputs and abatement levels are as follows:[14]

$$x_{\{i\}} = x_{\{j \neq i\}} = \frac{A - t}{(1+n)b} \text{ and } a_{\{i\}} = a_{\{j \neq i\}} - \frac{u}{g} = \frac{t}{g} - \frac{u}{g}. \tag{16}$$

Learning the value of the shock over the abatement costs of firm $i$ does not affect the output decisions of the rivals since the output of firm $i$ does not depend on the shock. Moreover, decisions regarding abatement are independent. Therefore, no discrimination regarding learning is needed.

Again solving backwards at $\tau = 3$ the regulator determines the optimal updated tax. It follows:

*Remark 6* $t_u^* > 0$.

The policy responds positively in the shock over the abatement cost function as in the single firm case. When the regulator remains uninformed it follows that $t_u^{**} = 0$.

Similarly to the case of standards the following proposition introduces the additional effect over convexity of profits in the presence of $n$ firms:

**Proposition 5** *Given the linear specification, the introduction of n firms reduces the convexity of profits with respect to u.*

Contrary to the case of standards, now, the introduction of multiple firms reduces convexity when firm $i$ reveals the value of the shock. A positive shock translates to a higher tax and this in turn affects negatively the output of the rival firms. Due to the negative slope of the inverse demand function the overall sign is positive. Since the subgame equilibrium output of firm $i$ also depends negatively on $u$, convexity is reduced and therefore the firm has an even stronger incentive to hide information compared to the corresponding single firm case.

[14] For simplicity we keep the same notation as in the case of standards.

Therefore, in terms of information disclosure, the introduction of many firms does not change the results. On the contrary the results are even stronger. Since in any case the corresponding policy is not tailored to each firm separately regulation is indeed sub-optimal. On the one hand, there is an advantage of quantities over prices as the first imply regulation under complete information versus uncertainty implied when prices are implemented. On the other hand, prices have an advantage relative to quantities in terms of allocative efficiency. Therefore, a trade-off between prices and quantities as in Weitzman is present. Yet, compared to Weitzman we shall expect that there is an extra bias favoring quantities.

Thus far, we have focused on the case where the shock over the abatement cost is private for one firm. Naturally, our model extends to the case where each firm faces a private shock, i.e., we have $n$ independent shocks. However, there is no reason to believe that this is the unique scenario. It may well be that the firms' private shocks are correlated or even that the shock is common across firms. In the latter case, a regulator could resolve the problem of incomplete information exploiting yardstick competition. Yet, even if this is not feasible our results will hold invariably following our standard arguments. In particular, when quantities are implemented regulation depends positively on the shock as the regulator has an incentive to relax the standard when costs are higher and the reverse. Therefore, expected profits remain higher under complete rather than under incomplete information and thus information disclosure occurs. Similarly, when prices are in place regulation depends positively on the shock. Higher marginal abatement costs imply a higher tax and vice-versa. This in turn reduces further the incentive of the firm to disclose information. We shall expect that the cases of correlated costs will stand in between of the two extreme cases, i.e., private and common shock.[15]

### 5.2 Verifiability and Limited Commitment

As previously highlighted the firm enters the agreement before learning the true state. When the state of nature results in stricter policy the firm has a clear incentive to misreport the true state. Therefore, if information is partially verifiable the analysis differs. In case that the participants enter an agreement then it is important to determine the mode of regulatory adjustment. In particular, if the regulator adjusts the level of regulation according to the actual value of the verified shock, then the answer regarding information disclosure needs further investigation.[16] From the firm's side, naturally, the incentive to enter an agreement (present in the case of standards) should be even stronger because of the possibility to misreport. On the other hand, it is not clear whether the regulator wants to sign an agreement when information is only partially verifiable.

We first focus on standards and abstract from the decision of the firm. The results obtained for the linear specification are clear but cumbersome. For brevity we summarize them in Fig. 4a. On the horizontal axis we introduce the probability $\phi$, which is the probability that the regulator learns the true value of the shock after inspecting. Learning happens at a later point in time. On the vertical axis the difference of expected welfare levels between the cases where the two counterparts sign the agreement and when they do not is presented. The correlation between the difference in expected welfare levels and $\phi$ is positive following standard intuition. Here, it is important to note that the results do not depend qualitatively on

[15] The results regarding the common shock can be provided upon request.

[16] Note that if the outcome of the inspection does not reveal any information to the regulator, then regulation adjusts according to the initial (false) statement of the firm.

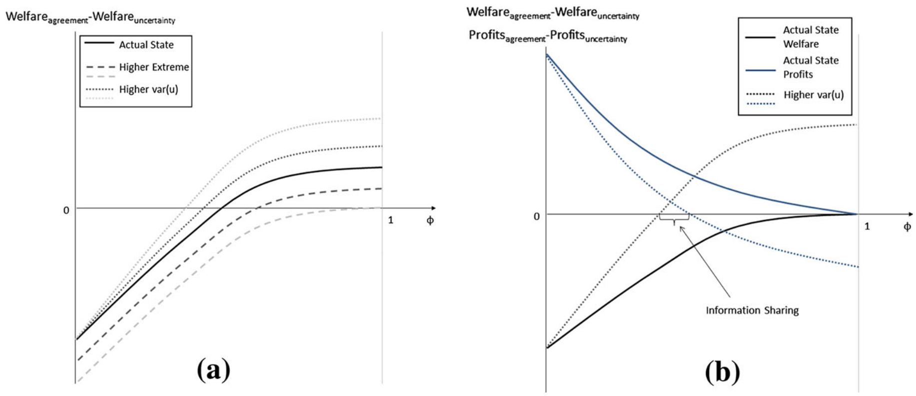


**Fig. 4** Incentives to participate in an agreement with limited verifiability. **a** Standards, **b** Taxes

the values of the various parameters of the model, but only on the variance of the shock and the magnitude of the shock.

In Fig. 4a we draw a solid line corresponding to some fixed values of the parameters and $\text{var}(u) < u_H^2$, where $u_H$ denotes the highest value of the shock. The variance of the shock should always be less or equal (in case of a binary shock) than the quadratic value of the latter one. Higher values of $u_H$ shift the curve downwards (see heavy dotted curves). As this curve fades out it implies an even higher value of $u_H$. The higher the magnitude of the shock the higher must be the value of $\phi$ for which the regulator enters the agreement. This is implied by the negative relation between the expected welfare under an agreement and $u_H$. High values of $u_H$ imply a higher regulatory distortion in case of misreport. Hence, the regulator will sign an agreement only if the probability of verifying the true value is relatively high, i.e., high $\phi$.

On the contrary, an increase in $\text{var}(u)$ implies an anti-clockwise shift of the curve (see thin dotted curves). As this curve fades out it translates to a higher $\text{var}(u)$. As volatility increases the flexibility implied by the agreement leads to higher expected welfare. The idea is closely related to the analysis regarding the firm's benefits from flexibility. Hence, when volatility increases the cut-off value of $\phi$ for which signing an agreement is *ex ante* preferred by the regulator is reduced. Naturally, as $\phi$ tends to zero the role of the variance vanishes since the additional benefits from flexibility disappear.

Our calculations suggest that limited verifiability can deter the regulator to participate in an agreement when the difference between $\text{var}(u)$ and $u_H^2$ is rather large. This may occur when the shock takes values in a continuous space. Even in this case there are values of $\phi$ close yet strictly less than one for which the regulator signs the agreement. As $\text{var}(u)$ and $u_H^2$ converge, the cut-off value of $\phi$ reduces significantly. This in turn implies that the regulator is willing to set an agreement even when information is not very likely to be verified. From a regulatory point of view this would be clearly sub-optimal.

The analysis regarding taxes is presented in Fig. 4b. The discussion regarding the differences in expected welfare levels is similar to the one for the case of standards. We select as a starting point $\text{var}(u) = 0$. Therefore, only when $\phi = 1$ the two expected welfare levels are equal. For $\phi < 1$ the regulator is not willing to sign an agreement. This changes when $\text{var}(u) > 0$ which translates to an anti-clockwise shift of the curve (black/positively sloped dotted curve). Now, there exists a range of values of $\phi$ for which the regulator is willing to sign an agreement.

To conclude whether an agreement between the two counterparts is signed or not we must study the behavior of the firm. For $\mathrm{var}(u) = 0$, the difference of expected profits with and without an agreement is always positive (blue/negatively sloped solid curve). As $\mathrm{var}(u) > 0$ the firm is less willing to participate into the agreement. This follows directly from the corresponding analysis for the firm throughout the paper. However, for $\varphi < 1$ the firm might want to participate (see blue/negatively sloped dotted curve).

An agreement regarding information sharing between the regulator and the firm occurs only for the overlapping values of $\phi$ for which both benefit from the agreement. From Fig. 4b we observe that this only happens for a rather narrow range of values of $\phi$, yet it can even vanish for different parameter constellations and different values of $\mathrm{var}(u)$. Therefore, limited verifiability may induce the firm to participate into an agreement only because the firm is given the opportunity to misreport, announcing negative values for the shock as this results to a lower tax. Similarly to standards limited verifiability distorts regulation and thus is also sub-optimal.

The possibility that the regulator is misinformed by the firm when the verification process fails to reveal the true information distorts regulation away from the socially desired level. This in turn it creates a trade-off for the regulator. On the one hand the regulator benefits when the true state is revealed, whereas on the other hand the regulator is worse off when the received information is imprecise, as in this case regulation adjusts to the false statement of the firm. At this point it should be clear that under the presence of limited verifiability regulation alone does not solve the problem of misreporting.

The problem of limited commitment of the firm stems from the limited verifiability of information. One way to eliminate this problem is to propose a scheme where quantities are combined with prices so that truthful revelation is incentive compatible (e.g., Lewis 1996; Montero 2008). However, the current scheme is much simpler. Following Baron and Besanko (1984) the problem disappears as soon as a fine-penalty for misreporting is introduced.[17] The fine for misreporting should be announced when the agreement is signed, i.e., $\tau = 1$. Misreporting incentives disappear when a fine is set:

$$F \geq E\left[\pi^{m}(\phi)\right] - E\left[\pi^{tr}\right] \equiv F^{*}, \tag{17}$$

where $E\left[\pi^{m}(\phi)\right]$ stands for expected profits when the firm misreports and $E\left[\pi^{tr}\right]$ for expected profits when the firm reports truthfully. Thus, if the firm agrees *a priori* to pay a fine larger or equal than the expected gain from misreporting then *ex post* will never do so since it will report truthfully. $E\left[\pi^{m}(\phi)\right]$ depends negatively on $\phi$, as a higher probability of learning the truth reduces the benefits from misreporting. In this case there is also an inverse relationship between the minimum required fine $F^{*}$, and $\phi$.

To sum up the regulator offers a contract $\{z^{*}, F^{*}\}$ which induces truth telling and in turn the regulator sets the standard as if regulating under complete information. From a policy perspective it may be difficult to determine the exact level of $F^{*}$. However, from Eq. (17) it is apparent that it suffices to announce a relatively high fine which will not be paid *ex post* as the firm reports truthfully.

## 6 Concluding Remarks

In this paper we explore the properties of the profit functions under various modes of uncertainty and different modes of regulation. We illustrate that in the presence of abatement cost

[17] For simplicity it is assumed that the regulator commits to inspect (audit) the firm. This is the case when auditing cost is rather small. However, even when there is a significant auditing cost and the regulator cannot commit in auditing, truth-telling can still be obtained (Khalil 1997).

and of demand uncertainty, quantities are preferred over prices because the uncertainty problem is endogenously resolved. The presence of multiple firms strengthens the incentives of the firms to disclose information when quantities are implemented regardless of the fact that the rival firms remain uninformed or not. Moreover, if information is not fully verifiable by the regulator it suffices to impose a fine for misreporting to eliminate the incentives to do so. The results extend to the case when the market power of firms converges to zero.

A great deal remains to be done to extend the results or eliminate any possible limitations of the current modeling. Future works may consider explicitly a case where the regulator delegates a third-party mediator to audit the firm and information cannot be extracted completely or, alternatively, it is costly to do so. We would expect that the positive bias in favor of quantities remains. Hence, it may be informative to express the Weitzman rule as a function of the probability or the fixed costs of extracting the true information.

In addition to our results, we shall expect that if the firms are also uncertain about the future mode of regulation, then it is very likely that they will not agree to disclose information. Put differently, if the regulatory risk is sufficiently high then information disclosure may not occur.[18] Exploring the interrelation between these two modes of uncertainties could potentially lead to useful conclusions. Finally, uncertainty over the slopes of marginal abatement costs or the slope of demand are not considered here. We do believe, however, that the basic mechanism can be still applied to these cases as well.

## Appendix

*Proof of Remark 1* (a) To obtain $z_u^*$ we differentiate (6) with respect to $u$ given that $z(u)$ and $x(u, z(u))$. Then it follows that $z_u^* = -\left(\frac{1-x_z+x_z[-1+(v_{xx}-c_{xx})x_u]}{w_{zz}} + \frac{(v_x-c_x)x_{zu}}{w_{zz}}\right)$. Using (5) we obtain $1 - x_z + x_z\left[-1 + (v_{xx} - c_{xx})\, x_u\right] = \frac{-c_{xx}v_{xx}+(2v_{xx}+xv_{xxx})^2}{\pi_{xx}^2} > 0 \Rightarrow \frac{1-x_z+x_z[-1+(v_{xx}-c_{xx})x_u]}{w_{zz}} < 0$. From Young's Theorem we have $x_{zu} = x_{uz}$. After differentiating $x_u$ given in (5) with respect to $z$ we obtain $x_{uz} = \frac{(x_z-1)c_{xxx}-x_z(3v_{xxx}+xv_{xxxx})}{\pi_{xx}^2}$.

(b) Differentiate (6) with respect to $\theta$ given that $z(\theta)$ and $x(\theta, z(\theta))$. Then it follows that $z_\theta^* = -\left(\frac{x_z(2-x_z+v_{xx}x_\theta)}{w_{zz}} + \frac{(v_x-c_x)x_{z\theta}}{w_{zz}}\right)$. Using (5) we obtain $(2 - x_z + v_{xx}x_\theta) = \left(2 - \frac{v_{xx}-c_{xx}}{\pi_{xx}}\right) > 0$ and $x_{z\theta} = x_{\theta z} = \frac{(1-x_z)c_{xxx}+x_z(3v_{xxx}+xv_{xxxx})}{\pi_{xx}^2}$. □

*Proof of Remark 2* (a) From $E[u] = 0$ and $E[x_u] = 0$ it follows directly that $z_u^{**} = 0$.

(b) From $E[\theta] = 0$ and $E[x_\theta] = 0$ it follows directly that $z_\theta^{**} = 0$. □

*Proof of Proposition 1* Define as $x_u^* = x_u + x_z z_u^*$, $a_u^* = x_u^* - z_u^*$, $x_\theta^* = x_\theta + x_z z_\theta^*$ and $a_\theta^* = x_\theta^* - z_\theta^*$. After differentiating (2) with respect to $u$ and using envelope we obtain

$$\left\{\begin{array}{l} \pi_u = -c_z z_u^* - a \Rightarrow \\ \pi_{uu} = \left(-c_{zx}x_u^* - c_{zz}z_u^* - c_{zu}\right) z_u^* - a_u^* - c_z z_{uu}^* = (c_{aa}a_u^* + 2)z_u^* - x_u^* + c_a z_{uu}^* \text{ and} \\ \pi_\theta = -c_z z_\theta^* + x \Rightarrow \\ \pi_{\theta\theta} = \left(-c_{zx}x_\theta^* - c_{zz}z_\theta^*\right) z_\theta^* + x_\theta^* - c_z z_{\theta\theta}^* = c_{aa}a_\theta^* z_\theta^* + x_\theta^* + c_a z_{\theta\theta}^* \end{array}\right\}. \tag{18}$$

[18] Strausz (2011) investigates the specific conditions under which a monopolist is hurt from the presence of regulatory risk.

Using Remark 2 we obtain $z_u^{**} = 0$ and $z_\theta^{**} = 0$. It follows that $x_u^* = x_u$ and $x_\theta^* = x_\theta$. Substituting these to (18) it follows that

$$\pi_u^{un} = -a \Rightarrow \pi_{uu}^{un} = -x_u \text{ and } \pi_\theta^{un} = x \Rightarrow \pi_{\theta\theta}^{un} = x_\theta. \tag{19}$$

Comparing the second derivatives of the profit functions in (18) and (19) and using the results in (5) we obtain:

$$\pi_{uu} - \pi_{uu}^{un} = \underbrace{(x_z - 1)\left(c_{aa} z_u^* - 2\right) z_u^*}_{\text{(unknown)}} + \underbrace{c_a}_{(+)} \underbrace{z_{uu}^*}_{\text{(unknown)}} \gtreqless 0 \text{ and} \tag{20a}$$

$$\pi_{\theta\theta} - \pi_{\theta\theta}^{un} = \underbrace{\left[c_{aa}(x_z - 1) z_\theta^* + 2x_z\right] z_\theta^*}_{\text{(unknown)}} + \underbrace{c_a}_{(+)} \underbrace{z_{\theta\theta}^*}_{\text{(unknown)}} \gtreqless 0. \tag{20b}$$

(a) From (20a) we get that $(x_z - 1)\left(c_{aa} z_u^* - 2\right) > 0$ when $z_u^* \in \left(0, \frac{2}{c_{aa}}\right)$. For $x_{zu} \simeq 0 \Rightarrow z_u^* - \frac{2}{c_{aa}} = -\frac{1}{c_{aa}} - \frac{d_{zz}\pi_{xx}^2}{d_{zz}\pi_{xx}^2 + c_{aa}\left[(2v_{xx} + xv_{xxx})^2 - c_{aa}v_{xx}\right]} < 0$. Therefore $z_{uu}^* > -\frac{(x_z-1)\left(c_{aa}z_u^*-2\right)z_u^*}{c_a} \Leftrightarrow \pi_{uu} - \pi_{uu}^{un} > 0$.

At $u = 0$ it holds $\pi = \pi^{un}$ and $0 > \pi_u > \pi_u^{un}$. We select $\underline{u} = -\varepsilon$ and $\overline{u} = \varepsilon$, $\varepsilon > 0$. The intercept of the straight line that connects $\pi(\underline{u})$ and $\pi(\overline{u})$ corresponds to the expected value of profits under complete information. That is, $E[\pi] = \frac{\pi(\underline{u})+\pi(\overline{u})}{2}$. Similarly, the intercept of the straight line that connects $\pi(\underline{u})^{un}$ and $\pi(\overline{u})^{un}$ corresponds to the expected value of profits under incomplete information. That is, $E[\pi^{un}] = \frac{\pi(\underline{u})^{un}+\pi(\overline{u})^{un}}{2}$. Given that $\pi_{uu} > \pi_{uu}^{un} \Rightarrow \left|\pi(\underline{u}) - \pi(\underline{u})^{un}\right| < \left|\pi(\overline{u}) - \pi(\overline{u})^{un}\right|$ and $\pi(\underline{u}) < \pi(\underline{u})^{un}$, $\pi(\overline{u}) > \pi(\overline{u})^{un}$. Then it follows that $E[\pi] - E[\pi^{un}] = \frac{\pi(\underline{u})-\pi(\underline{u})^{un}+\pi(\overline{u})-\pi(\overline{u})^{un}}{2} > 0$.

(b) From (20b) we get that $\left[c_{aa}(x_z - 1) z_\theta^* + 2x_z\right] z_\theta^* > 0$ when $z_\theta^* \in \left(0, \frac{2x_z}{c_{aa}(1-x_z)}\right)$. For $x_{z\theta} \simeq 0 \Rightarrow z_\theta^* - \frac{2x_z}{c_{aa}(1-x_z)} = \frac{x_\theta\left\{2d_{zz}\pi_{xx}^2 + c_{aa}\left[2v_{xx}^2 + x(c_{aa}+v_{xx})v_{xxx}\right]\right\}}{(c_{aa}x_\theta - 1)\left\{\pi_{xx}^2 d_{zz} + c_{aa}\left[(2v_{xx}+xv_{xxx})^2 - c_{xx}v_{xx}\right]\right\}} < 0$ as $c_{aa}x_\theta - 1 < 0$ and all the remaining terms are positive. Therefore $z_{\theta\theta}^* > -\frac{\left[c_{aa}(x_z-1)z_\theta^*+2x_z\right]z_\theta^*}{c_a} \Leftrightarrow \pi_{\theta\theta} - \pi_{\theta\theta}^{un} > 0$. The rest of the proof is similar to part (a) and is omitted for brevity. □

*Proof of Remark 3* (a) To obtain $t_u^*$ we differentiate (12) with respect to $u$ given that $t(u)$, $x(t(u))$ and $a(u, t(u))$. Then it follows that $t_u^* = \frac{z_t d_{zz} a_t}{w_{tt}} - \frac{(c_a - d_z)a_{tt}}{w_{tt}}$. Using (11) it follows directly that $\frac{z_t d_{zz} a_t}{w_{tt}} > 0$. From Young's Theorem we have $a_{tu} = a_{ut}$. After differentiating $a_t$ given in (11) with respect to $t$ we obtain $a_{tt} = -\frac{a_t^2 c_{aaa}}{c_{aa}}$. Hence, the sign depends on the sign of $c_{aaa}$.

(b) To obtain $t_\theta^*$ we differentiate (12) with respect to $\theta$ given that $t(\theta)$, $x(\theta, t(\theta))$ and $a(t(\theta))$. Then it follows that $t_\theta^* = -\left(\frac{x_t(1+z_t d_{zz} - v_{xx}x_t)}{w_{tt}} - \frac{(v_x - d_z)x_{tt}}{w_{tt}}\right)$, where $x_{tt} = -\frac{x_t(3v_{xxx}+xv_{xxxx})}{\pi_{xx}^2}$. For $\frac{x_t(1+z_t d_{zz} - v_{xx}x_t)}{w_{tt}} < 0$ it suffices to show that $(z_t d_{zz} - v_{xx}x_t) < -1$ which holds true when $t^* > 0$. The latter is indeed the case when the benefits for a positive level of abatement exceed the costs, i.e., $\min\left[-2v_{xx} - xv_{xxx}, c_{aa}\right] < d_{zz}$. □

*Proof of Remark 4* (a) From $E[u] = 0$ and $E[a_u] = 0$ it follows directly from (14) that $t_u^{**} = 0$.

(b) From $E[\theta] = 0$ and $E[x_\theta] = 0$ it follows directly from (14) that $t_\theta^{**} = 0$. □

*Proof of Proposition 2* Define as $x_u^* = x_t t_u^*$, $a_u^* = a_u + a_t t_u^*$, $x_\theta^* = x_\theta + x_t t_\theta^*$ and $a_\theta^* = a_t t_\theta^*$. After differentiating (2) with respect to $u$ and using envelope we obtain

$$\left\{\begin{array}{l} \pi_u^t = -a - (x-a)\, t_u^* \Rightarrow \\ \pi_{uu}^t = -a_u^* - \left(x_u^* - a_u^*\right) t_u^* - (x-a)\, t_{uu}^* = -a_u^*\left(1 - t_u^*\right) - x_u^* t_u^* - (x-a)\, t_{uu}^* \text{ and} \\ \pi_\theta^t = x - (x-a)\, t_\theta^* \Rightarrow \\ \pi_{\theta\theta}^t = x_\theta^* - \left(x_\theta^* - a_\theta^*\right) t_\theta^* - (x-a)\, t_{\theta\theta}^* \end{array}\right\}. \tag{21}$$

Using Remark 4 we obtain $t_u^{**} = 0$ and $t_\theta^{**} = 0$. It follows that $a_u^* = a_u\ and a_\theta^* = a_\theta$. Substituting these to (21) it follows that

$$\pi_{uu}^{t,un} = -a_u \text{ and } \pi_{\theta\theta}^{t,un} = x_\theta. \tag{22}$$

Comparing the second derivatives of the profit functions in (21) and (22) we obtain:

$$\pi_{uu}^t - \pi_{uu}^{t,un} = \underbrace{-\left(2a_t + z_t t_u^*\right) t_u^*}_{\text{(unknown)}} - \underbrace{(x-a)}_{(+)} \underbrace{t_{uu}^*}_{\text{(unknown)}} \gtreqless 0 \text{ and} \tag{23a}$$

$$\pi_{\theta\theta}^t - \pi_{\theta\theta}^{t,un} = \underbrace{\left(2x_t - z_t t_\theta^*\right) t_\theta^*}_{(-)} - \underbrace{(x-a)}_{(+)} \underbrace{t_{\theta\theta}^*}_{\text{(unknown)}} \gtreqless 0. \tag{23b}$$

(a) From (23a) we get that $-\left(2a_t + z_t t_u^*\right) t_u^* < 0$ when $t_u^* \in \left(0, -\frac{2a_t}{z_t}\right)$. For $a_{tt}, x_{tt} \simeq 0 \Rightarrow t_u^* + \frac{2a_t}{z_t} < t_u^* + \frac{a_t}{z_t} = \frac{1}{z_t} \frac{\pi_{xx}^2 - c_{aa} v_{xx}}{c_{aa}^2 (d_{zz} - v_{xx}) - c_{aa}(2d_{zz} - \pi_{xx})\pi_{xx} + d_{zz}\pi_{xx}^2} < 0$. Therefore $t_{uu}^* > \frac{-(2a_t + z_t t_u^*) t_u^*}{x-a} \Leftrightarrow \pi_{uu}^t - \pi_{uu}^{t,un} < 0$. At $u = 0$ it holds $\pi^t = \pi^{t,un}$ and $0 > \pi_u^{t,un} > \pi_u^t$. We select $\underline{u} = -\varepsilon$ and $\overline{u} = \varepsilon$, $\varepsilon > 0$. The intercept of the straight line that connects $\pi(\underline{u})^t$ and $\pi(\overline{u})^t$ corresponds to the expected value of profits under complete information. That is, $E[\pi^t] = \frac{\pi(\underline{u})^t + \pi(\overline{u})^t}{2}$. Similarly, the intercept of the straight line that connects $\pi(\underline{u})^{t,un}$ and $\pi(\overline{u})^{t,un}$ corresponds to the expected value of profits under incomplete information. That is, $E[\pi^{t,un}] = \frac{\pi(\underline{u})^{t,un} + \pi(\overline{u})^{t,un}}{2}$. Given that $\pi_{uu}^t < \pi_{uu}^{t,un} \Rightarrow \left|\pi(\underline{u})^{t,un} - \pi(\underline{u})^t\right| < \left|\pi(\overline{u})^{t,un} - \pi(\overline{u})^t\right|$ and $\pi(\underline{u})^t > \pi(\underline{u})^{t,un}$, $\pi(\overline{u})^t < \pi(\overline{u})^{t,un}$. Then it follows that $E[\pi^t] - E[\pi^{t,un}] = \frac{\pi(\underline{u})^t - \pi(\underline{u})^{t,un} + \pi(\overline{u})^t - \pi(\overline{u})^{t,un}}{2} < 0$.

(b) From (23b) we get that $\left(2x_t - z_t t_\theta^*\right) t_\theta^* < 0$ when $t_\theta^* \in \left(0, \frac{2x_t}{z_t}\right)$. For $a_{tt} \simeq 0 \Rightarrow t_\theta^* - \frac{2x_t}{z_t} < t_\theta^* - \frac{x_t}{z_t} = \frac{1}{z_t} \frac{c_{aa}(c_{aa} - \pi_{xx} - v_{xx} - x v_{xxx})}{c_{aa}^2 (d_{zz} - v_{xx}) - c_{aa}(2d_{zz} - \pi_{xx})\pi_{xx} + d_{zz}\pi_{xx}^2} < 0$ as $-v_{xx} - x v_{xxx} > 0$ from the necessary condition for $t^* > 0$. Therefore $t_{\theta\theta}^* > \frac{(2x_t - z_t t_\theta^*) t_\theta^*}{x-a} \Leftrightarrow \pi_{\theta\theta}^t - \pi_{\theta\theta}^{t,un} < 0$. The rest of the proof is similar to part a) and is omitted for brevity. □

*Proof of Proposition 3* From Proposition 1 it follows that when a standard is implemented information sharing occurs when $z_u^* > 0$ and $z_\theta^* > 0$ given that $z_{uu}^*, z_{\theta\theta}^* \simeq 0$. From Proposition 2 it follows that when a tax is implemented information sharing does not occur when $t_u^* > 0$ and $t_\theta^* > 0$ given that $t_{uu}^*, t_{\theta\theta}^* \simeq 0$. In terms of pollution it corresponds $z_u^* = x_u^* - a_u^* = x_t t_u^* - a_u - a_t t_u^* = z_t t_u^* + a_t > 0$ since from Proposition 2(a) we have $t_u^* + \frac{a_t}{z_t} < 0$. Similarly, for $z_\theta^* = x_\theta^* - a_\theta^* = x_\theta + x_t t_\theta^* - a_t t_\theta^* = z_t t_\theta^* - x_t > 0$ since from Proposition 2(b) we have $t_\theta^* - \frac{x_t}{z_t} < 0$. □

*Proof of Remark 5* We first define $\zeta \equiv g^2kn+b^2(1+n)^2(g+kn)+bgn\,[g+2k(1+n)] > 0$. The welfare function given in (3) translates to

$$w = AX - \frac{1}{2}bX^2 - \frac{1}{2}g\left(x_{\{i\}} - z\right)^2 - \left(x_{\{i\}} - z\right)u - \frac{1}{2}(n-1)\,g\left(x_{\{j\neq i\}} - z\right)^2 - \frac{1}{2}k(nz)^2, \tag{24}$$

where $X \equiv (n-1)x_{\{j\neq i\}} + x_{\{i\}}$. Given (15) the first order condition for welfare maximization $\frac{dw}{dz} = 0 \Rightarrow$

$$z^* = z^*_{\{u=0\}} + \frac{b(b+g+bn)\,[gn+2b(1+n)]}{(2b+g)n\zeta}u \text{ and } z^{l*} = z^*_{\{u=0\}} + \frac{b\left[gn+b(1+n)^2\right]}{n\zeta}u, \tag{25}$$

where $z^*_{\{u=0\}} \equiv \frac{Ag[g+b(2+n)]}{\zeta}$. From (25) it follows that $z^*_u > 0$ and $z^{l*}_u > 0$.

*Proof of Proposition 4* After differentiating the profit function with respect to $u$ and using envelope without and with learning we obtain correspondingly

$$\left\{\begin{array}{l}
\pi_u = -c_z z^*_u - a_{\{i\}} - b\,(n-1)\,\frac{\partial x_{\{j\neq i\}}}{\partial z} z^*_u x_{\{i\}} \Rightarrow \\
\pi_{uu} = (c_{aa}\frac{\partial a^*_{\{i\}}}{\partial u} + 2)z^*_u - \frac{\partial x^*_{\{i\}}}{\partial u} \underbrace{-b\,(n-1)\,\frac{\partial x_{\{j\neq i\}}}{\partial z} z^*_u \frac{\partial x^*_{\{i\}}}{\partial u}}_{\text{Effect of multiple firms }(+)} \text{ and} \\
\pi^l_u = -c_z z^{l*}_u - a^l_{\{i\}} - b\,(n-1)\,\frac{\partial x^l_{\{j\neq i\}}}{\partial z} z^{l*}_u x^l_{\{i\}} - b\,(n-1)\,\frac{\partial x^l_{\{j\neq i\}}}{\partial u} x^l_{\{i\}} \Rightarrow \\
\pi^l_{uu} = (c_{aa}\frac{\partial a^{l*}_{\{i\}}}{\partial u} + 2)z^{l*}_u - \frac{\partial x^{l*}_{\{i\}}}{\partial u} \underbrace{-b\,(n-1)\,\frac{\partial x^l_{\{j\neq i\}}}{\partial z} z^{l*}_u \frac{\partial x^{l*}_{\{i\}}}{\partial u} - b\,(n-1)\,\frac{\partial x^l_{\{j\neq i\}}}{\partial u}\frac{\partial x^{l*}_{\{i\}}}{\partial u}}_{\text{Effect of multiple firms }(+)}
\end{array}\right\}. \tag{26}$$

From (26) we observe that the additional effects due to the presence of multiple firms compared to the corresponding ones in the single firm case of Proposition 1 are positive. To show that, we employ (15) and (25) where it follows $\frac{\partial x_{\{j\neq i\}}}{\partial z}, \frac{\partial x^l_{\{j\neq i\}}}{\partial z}, \frac{\partial x^l_{\{j\neq i\}}}{\partial u} > 0$ and $z^*_u, z^{l*}_u > 0$. It remains to show that $\frac{\partial x^*_{\{i\}}}{\partial u}, \frac{\partial x^{l*}_{\{i\}}}{\partial u} < 0$ which are derived after replacing Eqs. (25) into (15). Once the additional effects are positive they augment the results obtained in the single firm case regarding convexity. □

*Proof of Remark 6* The welfare function given in (3) translates to

$$w = AX - \frac{1}{2}bX^2 - \frac{1}{2}ga^2_{\{i\}} - a_{\{i\}}u - \frac{1}{2}(n-1)\,ga^2_{\{j\neq i\}} - \frac{1}{2}k\left[X - a_{\{i\}} - (n-1)\,a_{\{j\neq i\}}\right]^2, \tag{27}$$

where $X \equiv (n-1)x_{\{j\neq i\}} + x_{\{i\}}$. Given (16) the first order condition for welfare maximization $\frac{dw}{dz} = 0 \Rightarrow$

$$t^* = t^*_{\{u=0\}} + \frac{(b+g+bn)bk(1+n)}{\zeta}u, \tag{28}$$

where $t^*_{\{u=0\}} \equiv \frac{Ag[gkn+b(-g+kn(1+n))]}{\zeta}$. From (28) it follows that $t^*_u > 0$. □

*Proof of Proposition 5* After differentiating the corresponding profit function with respect to $u$ and using envelope we obtain

$$\left\{ \begin{array}{l} \pi_u^t = -a_{\{i\}} - \left(x_{\{i\}} - a_{\{i\}}\right) t_u^* - b\,(n-1)\,\frac{\partial x_{\{j\neq i\}}}{\partial t} t_u^* x_{\{i\}} \Rightarrow \\ \pi_{uu}^t = -\frac{\partial a_{\{i\}}}{\partial u}\left(1 - t_u^*\right) - \frac{\partial x_{\{i\}}^*}{\partial u} t_u^* \underbrace{-b\,(n-1)\,\frac{\partial x_{\{j\neq i\}}}{\partial t} t_u^* \frac{\partial x_{\{i\}}^*}{\partial u}}_{\text{Effect of multiple firms } (-)} \end{array} \right\}. \tag{29}$$

From (29) we observe that the additional effect due to the presence of multiple firms compared to the corresponding one in the single firm case of Proposition 2 is negative. To show that, we employ (16) and (28) where it follows $\frac{\partial x_{\{j\neq i\}}}{\partial t}, \frac{\partial a_{\{i\}}}{\partial u} < 0$ and $t_u^* > 0$. It remains to show that $\frac{\partial x_{\{i\}}^*}{\partial u} < 0$ which follows after replacing Eq. (28) into (16). Once the additional effect is negative the convexity of the profit function is reduced. □

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