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Working Paper

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Economics Working Paper Series, No. 16/263

Provided in Cooperation with:

ETH Zurich, CER-ETH – Center of Economic Research

Suggested Citation: Ing, Julie (2016) : Adverse selection, commitment and exhaustible resource taxation, Economics Working Paper Series, No. 16/263, ETH Zurich, CER-ETH - Center of Economic Research, Zurich

This Version is available at:

<https://hdl.handle.net/10419/171706>

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CER-ETH – Center of Economic Research at ETH Zurich

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Working Paper 16/263
December 2016

Economics Working Paper Series



Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Adverse selection, commitment and exhaustible resource taxation

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Abstract

Governments design taxation schemes to capture resource rent. However, they usually propose contracts with limited duration and possess less information on the resources than the extractive firms do. This paper investigates how information asymmetry on costs and an inability to commit to long-term contracts affect tax revenue and the extraction path. This paper assumes that governments maximize the tax revenue contingent on the quantity extracted. This study gives several unconventional results. First, when information asymmetry exists, the inability to commit does not necessarily lower tax revenues. Second, under asymmetric information without commitment, an efficient firm may produce during the first period more or less than under symmetric information. Hence, the inability to commit has an ambiguous effect on optimal contract duration. Third, an increase in the discount factor may shift the extraction towards the first period which contradicts Hotelling's rule.

Keywords: resource taxation; asymmetric information; commitment

JEL Classification: Q38, D86, H21

1 Introduction

Natural resource revenues are substantial and developing economies rely heavily on the tax receipts they generate. From 2000 to 2007, at least 70% of the government's revenue in Algeria and Angola

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came from hydrocarbons. Today, diamonds account for 76% of Botswana's export revenue, 45% of the government revenue and 33% of the gross domestic product. Despite the resource curse¹, natural resources are a remarkable opportunity to foster development and reduce poverty. Nevertheless, their taxation comes with significant challenges for many low-income countries. In regions that have yet to develop their natural resources, it will not be possible to establish national mining companies and exclude international companies and their expertise. Many governments delegate the exploitation of their natural resources to international private firms. However, designing the fiscal instrument is not an easy task since governments may lack information. As [Collier and Venables \(2010\)](#) and [Humphreys et al. \(2007\)](#) point out, governments usually possess less information on resource's geological settings and commercial value than firms undertaking exploration, development and extraction activities. Consequently, according to [Boadway and Keen \(2009\)](#), firms may understate resource stocks or overstate their costs. Similarly, [Osmundsen \(2009\)](#) claims that companies may act strategically by employing datasets and measurement methods that best serve their interests. As a result, governments should design taxation schemes that take extractive firms' strategic behavior into account.

In addition to this adverse selection problem, governments are usually unable to commit to long-term contracts. The non-commitment assumption is particularly relevant for mining industries. On the one hand, contracts are often renegotiated. For instance, from 2004-2007, the Venezuelan government increased royalties and income taxes and imposed joint ventures under government control ([Hogan and Sturzenegger \(2010\)](#), chapter 12). On the other hand, delegation contracts for the exploitation of natural resources are signed for a limited period of time. For instance, in October 2004, the Global Alumina Products Corporation and the Ministry of Mines and Geology of the Republic of Guinea signed a contract for the development of an alumina refinery in Conakry. This mining concession has an initial term of 25 years and may be renewed for 25 years. After these 50 years, a succession of ten year contracts is possible. Thus, natural resources are developed through a series of contracts.

¹The resource curse states that countries with an abundance of natural resources tend to have less economic growth and worse development outcomes than countries with fewer natural resources (see [Sachs and Warner \(2001\)](#), [Kolstad and Wiig \(2009\)](#) or [Robinson et al. \(2006\)](#))

In a nutshell, this paper investigates how an inability to commit to long-term contracts affects tax revenues and the extraction path when there is information asymmetry. This paper assumes that governments maximize the tax revenue without taking into account the firms' profit or the consumer surplus. Indeed, resource-rich countries delegate resource extraction to foreign companies and export a significant share of their resources. I assume that firms have private information on the extraction efficiency, this efficiency is constant over time. I only consider two types of firm, i.e. efficient or inefficient. Therefore, if the information is revealed during one period, there is symmetric information during the following periods. This paper compares the outcome of symmetric information and asymmetric information with and without commitment. This analysis disentangles the effects related to the exhaustibility of the resource from the effects related to the information flow and lack of commitment. The paper pays particular attention to the discount factor and its effects on the type of contracts implemented (separating, semi-separating or pooling contracts) and on the optimal extraction path. To simplify the analysis, I assume that under symmetric and asymmetric information, it is always optimal to exhaust the stock in the second period, thus I only consider two-period contracts. However, at the end of the paper, I discuss how information asymmetry may affect the optimal contract duration.

Introducing adverse selection into non-renewable resources models implies two types of dynamics. The first one is related to the resource stock, since future choices are constrained by current choices. The second one is related to the information, since the regulator updates its belief on the firm's type. To my knowledge, only a few papers study how information asymmetry affects the taxation scheme, the extraction path and thus Hotelling's rule.² This rule constitutes a central element in non-renewable resources theories, and shows how the price of resource should evolve along an optimal extraction path. Hotelling's rule requires that an increase in the discount factor decreases current extraction and increases future extraction. The three main contributions studying resource taxation with asymmetric information are summarized as follows. [Osmundsen \(1998\)](#) considers a two-period model where a firm has private information on the size of the stock

²[Gaudet and Lasserre \(2015\)](#) propose an interesting literature review on the subject

and on the extraction costs. He finds that at each period, the most efficient firm should produce the same as under symmetric information (the first best). On the contrary, due to the trade-off between informational rent and productive efficiency, an inefficient firm should produce less than the first best. Indeed, the inefficient firm's production is set at a low level to deter an efficient firm from lying and to decrease the informational rent. [Osmundsen \(1998\)](#) neutralizes the dynamics related to the resource stock and the effect related to the information flow by assuming full commitment and an asymptotic production cost function. [Gaudet et al. \(1995\)](#) also consider two periods but only information asymmetry on the extraction costs. They show that when it is not optimal for some types of firm to exhaust the stock, the most efficient firm may produce more than the first best. Despite the non-commitment assumption, they also neutralize the dynamics related to the information by assuming that the parameter that is subject to information asymmetry is not correlated over time. [Hung et al. \(2006\)](#) relax the two-period assumption, and find that the information asymmetry on costs extends the contract duration. They also show that just before exhaustion, firms may produce a higher quantity than the first best. Despite a constant efficiency parameter, they also neutralize the effect of the information flow by studying the full-commitment case. The present paper studies both dynamics by assuming that there is no commitment and that the parameter that is subject to information asymmetry is correlated over time. The aim of this paper is to define the optimal taxation scheme taking into account two imperfections observed in reality: private information and a lack of commitment.

Relaxing the full-commitment assumption has major effects on optimal taxation schemes ([Farhi et al. \(2012\)](#), [Brito et al. \(1991\)](#) or [Dillén and Lundholm \(1996\)](#)). Indeed, without commitment, if a regulated firm has private information, the regulator updates its belief at the end of each contract. If the parameter that is subject to information asymmetry is correlated over time, a firm knows that revealing its information jeopardizes the informational rents it receives in subsequent periods. This is the so-called ratchet effect. Therefore, a firm must receive a large upfront payment to reveal information. This payment increases with the discount factor: if a firm values the future highly, it must be significantly compensated to reveal its information. The literature

on non-commitment, such as [Freixas et al. \(1985\)](#), [Laffont and Tirole \(1988\)](#), [Laffont and Tirole \(1990\)](#) and [Dionne and Fluet \(2000\)](#) points out two important effects. First, all types of agent may have an incentive to lie. Indeed, during the first period an inefficient firm may also misrepresent its type in order to receive a large upfront payment and then leave the relationship. An inefficient firm has more incentive to adopt this strategy when the discount factor is high, since this induces a large upfront payment. If both types have the incentive to misrepresent themselves (countervailing incentives), then at equilibrium both incentive constraints bind. Second, in the first period, some pooling may be optimal. Indeed, a full separation during the first period implies that a high informational rent must be paid upfront. By pooling the firms, the regulator reduces the speed of information revelation and thus reduces the informational rent paid to efficient firms. Hence, as the discount factor increases, during the first period, the regulator is more willing to propose pooling or semi-separating contracts than full-separating contracts.

This paper's contribution is twofold. First, it extends the contract theory literature on non-commitment by introducing a stock constraint. Indeed, the limited stock of resource alters the trade-off between informational rent and productive efficiency. If the stock is exhausted, decreasing the inefficient firm's production to reduce the informational rent during one period necessarily increases the production and thus the informational rent during the other periods. Second, the paper contributes to the literature on resource taxation with information asymmetry by focusing on informational dynamics.

The main results of this paper are summarized as follows. First, if the discount factor is relatively low, only an efficient firm misrepresents its type, and the lack of commitment has no effect. Indeed in this case, separating firms in the first period does not affect extraction during the second period, and thus does not increase the informational rent related to this period. Consequently, the extraction path and tax revenue are the same with and without commitment. This contrasts with the traditional result that the inability to commit lowers tax revenue. Second, without commitment, the efficient firm's first-period extraction may be distorted upward or downward. Indeed, the

regulator may be willing to increase the efficient firm's first-period production to deter an inefficient firm from lying, or it may propose in the first period a pooling contract in which the extraction is set below the efficient firm's first-best level. This directly implies that without commitment, the efficient firm's contract duration may be longer, shorter or the same as with symmetric information. This result differs from previous studies in which, an efficient firm never produces less than the first best during the first period. Third, I find that when the discount factor is moderate, Hotelling's rule does not always hold. Indeed, an increase in the discount factor increases the informational rent related to the second period. To compensate, the regulator may increase the efficient firm's first-period extraction to prevent an inefficient firm from understating its costs, and it may also increase the inefficient firm's second-period extraction. Hence, an increase in the discount factor may increase first-period extractions.

This paper is organized as follows. Section 2 presents the model and assumptions. Section 3 characterizes the benchmarks, i.e. optimal contracts under symmetric information and under asymmetric information with commitment. In section 4, the allocation under asymmetric information without commitment is defined. The results are discussed in section 5. The proofs are relegated to an appendix at the end of the paper.

2 General settings

For all scenarios: symmetric information and asymmetric information with and without commitment, I consider in the main text the case in which it is optimal to extract a positive quantity during the first period, and to exhaust the stock during the second period.³ I assume that the resource is worthless after the second period, and thus, I restrict my attention to two-period contracts. At the end of the paper, I assume that firms may exhaust the stock during a third period in order to discuss how information asymmetry without commitment affects optimal contract duration, and thus the date of exhaustion.

³In appendix E, I study the case in which none of the firms exhaust the stock to identify the effect of the stock constraint. Nevertheless, more cases are possible. For instance, it may be optimal for an efficient firm to exhaust the stock, while it is not for an inefficient firm.

I deal with two periods: $t = \{1, 2\}$. The regulator delegates to a firm the production of a resource available in quantity S . The production cost function is given by:

$$C(\theta, q_t) = \theta q_t + \frac{b}{2} q_t^2 \quad (1)$$

The contract specifies a monetary transfer T_t and the quantity to extract q_t at each period. To simplify the problem, I assume that the country is a price taker in the world market. I define:

$$U(\theta, q_t, T_t, p_t) = p_t q_t - C(\theta, q_t) - T_t \quad (2)$$

The discount factor is denoted by $\delta \in [0, 1]$ and U_F and U_R denote respectively the firm and the regulator's payoff. During each period, the firm obtains the revenue net of production costs, and transfers a fixed amount to the regulator. The regulator receives the discounted sum of transfers. Therefore:

$$U_F = U(\theta, q_1, T_1, p_1) + \delta U(\theta, q_2, T_2, p_2) \quad (3)$$

$$U_R = T_1 + \delta T_2 \quad (4)$$

The two periods are linked through the resource stock. The stock constraint is given by:

$$q_1 + q_2 \leq S \quad (SC)$$

The following superscripts are used: FB for symmetric information, FC for asymmetric information with commitment, NC for asymmetric information without commitment.

3 Benchmarks

3.1 Symmetric information

The regulator maximizes its payoff subject to the firm's participation constraint and the stock constraint. The firm's outside opportunity is normalized to zero. This problem is set out and solved in appendix A. Under symmetric information, the regulator captures all of the revenue and sets the transfers at:

$$T_t^{FB} = p_t q_t - C(\theta, q_t) \quad (5)$$

Maximizing the discounted sum of transfers with respect to quantities defines the optimal extraction level. Under symmetric information, the stock is ultimately exhausted if it is relatively low and if, during each period, the price is relatively high compared to the firm's efficiency. The regulator captures the entire revenue. Hotelling's rule holds: an increase in the discount factor decreases the first-period extraction.

From this point on, I assume that the regulator does not know the extraction efficiency parameter θ . The firm may be efficient ($\underline{\theta}$) with probability ν_0 , or inefficient ($\bar{\theta}$) with the complementary probability. I define $\bar{\theta} - \underline{\theta} = \Delta\theta > 0$ as the size of the information asymmetry. If the regulator does not know the firm's efficiency, then first-best contracts cannot be used. Indeed, under such contracts, an efficient firm overstates its efficiency in order to receive the cost differential.

3.2 Asymmetric information and full commitment

The regulator commits to long-term contracts, and thus, full-separating contracts are optimal. At each period, it proposes a contract that specifies the production q_t and the transfer T_t that it receives. $(\underline{T}_t, \underline{q}_t)$ denotes the contract designed for an efficient firm and (\bar{T}_t, \bar{q}_t) denotes the contract designed for an inefficient firm. The regulator maximizes its payoff subject to the stock constraints and to the firms' incentive and participation constraints. The problem is set out and

solved in appendix A. At equilibrium, the transfers can be rewritten as:

$$\bar{T}_t^{FC} = \bar{T}_t^{FB} \quad (6)$$

$$\underline{T}_t^{FC} = \underline{T}_t^{FB} - \Delta \theta \bar{q}_t \quad (7)$$

The second-best contracts are such that an efficient firm extracts the first best at each period and receives an informational rent $\Delta \theta (\bar{q}_1 + \delta \bar{q}_2)$. Due to the trade-off between informational rent and productive efficiency, the regulator is willing to set the inefficient firm's extraction below the first best to reduce the informational rent. Indeed, by decreasing the inefficient firms' production, the inefficient firm's contracts become less attractive for an efficient firm.

Since the stock is exhausted, the regulator cannot decrease extraction during one period without increasing extraction during the other period. As a result, it is optimal to decrease the informational rent, and so to decrease the inefficient firm's extraction at the most valued period. Since $\delta < 1$, during the first period, the inefficient firms' production is distorted downward, while during the second period it is distorted upward.

Proposition 1 *Under asymmetric information with commitment,*

1. *an efficient firm extracts the first best during each period. An inefficient firm extracts less than the first best during the first period and more than the first best during the second period. Hotelling's rule holds for both types.*
2. *Due to the production distortion and the informational rent, the discounted expected tax revenue is lower than under symmetric information.*

Note that if the stock is not exhausted, an inefficient firm extracts a lower quantity than under the first best during each period. In the first period, the inefficient firm's production distortion is larger than when the stock is exhausted since the first-period distortion does no longer increase the second-period informational rent.

4 Asymmetric information and non commitment

When the regulator is unable to commit to long-term contracts, in the first period, implementing full-separating contracts may not be optimal. The regulator proposes during the first period, a contract designed for each type (semi-separating or full-separating contracts), or a pooling contract. The firm chooses a contract and the regulator updates its belief accordingly. In the second period, the remaining stock is exhausted and the regulator proposes one contract for each type, or only the first best contract if it knows the firm's type. The regulator updates its prior belief (ν_0) according to a Bayesian rule. The posterior beliefs $\nu_1 = \{\underline{\nu}_1, \bar{\nu}_1\}$ are:

$$\underline{\nu}_1 = \frac{x \nu_0}{x \nu_0 + y (1 - \nu_0)} \quad \text{and} \quad \bar{\nu}_1 = \frac{(1-x) \nu_0}{(1-x) \nu_0 + (1-y) (1 - \nu_0)} \quad \text{with } x \in [0, 1] \text{ and } y \in [x, 1]$$

$\underline{\nu}_1$ is the probability that the firm is efficient knowing that $(\underline{q}_1, \underline{T}_1)$ is chosen.

$\bar{\nu}_1$ is the probability that the firm is efficient knowing that (\bar{q}_1, \bar{T}_1) is chosen.

x is the probability that an efficient firm chooses $(\underline{q}_1, \underline{T}_1)$ in the first period.

y is the probability that an inefficient firm chooses $(\underline{q}_1, \underline{T}_1)$ in the first period.

Without loss of generality, I assume that $x > y$.

The regulator's payoff is the weighted sum of the transfers that it might obtain:

$$\begin{aligned} U_R^{NC} = & (\nu_0 x + (1 - \nu_0) y) \underline{T}_1 + (\nu_0 (1 - x) + (1 - \nu_0) (1 - y)) \bar{T}_1 \\ & + \delta \left((\nu_0 x + (1 - \nu_0) y) (\underline{\nu}_1 \underline{T}_2 + (1 - \underline{\nu}_1) \bar{T}_2) + (\nu_0 (1 - x) + (1 - \nu_0) (1 - y)) (\bar{\nu}_1 \underline{T}_2 + (1 - \bar{\nu}_1) \bar{T}_2) \right) \end{aligned} \quad (8)$$

The values of x and y determine the type of contracts implemented in the first period:

Under full separation, each firm chooses the contract designed for its type: $(x, y) = (1, 0)$. The regulator identifies the type of firm it is dealing with. During the second period, $\underline{\nu}_1 = 1$ and $\bar{\nu}_1 = 0$, symmetric information occurs, the regulator captures all of the revenue.

Under semi separation, one type of firm plays a pure strategy, while the other plays a mixed strategy: $(x, y) = (1, y)$ or $(x, 0)$. In the second period, the regulator updates its belief. If in the first period, the contract chosen is designed for the type that plays a mixed strategy, then the regulator infers the firm's type. If not, information asymmetry still occurs.

Under a pooling contract, during the second period, no updating is possible since only one contract is proposed, $\underline{\nu}_1 = \bar{\nu}_1 = \nu_0$. Second-period contracts are similar to full-commitment ones.

The problem is solved backwards. First, for a given stock and updated beliefs, the contracts maximizing the expected tax revenue during the second period are determined. Second, taking for granted the second-period contracts, the first-period contracts maximizing the tax revenue are defined.

In the second period, both firms exhaust the remaining stock. The problem is the same as under full commitment, except that ν_0 is replaced by ν_1 . Indeed, with commitment the allocation is the same as the repetition of the optimal static contracts.

The first-period decisions affect the second-period contracts through the updated beliefs and the stock. The incentive and participation constraints take into account that during the second period, if information asymmetry still occurs, an inefficient firm has no rent and reveals its type, while an efficient firm is indifferent to lying or telling the truth, and receives an informational rent: $\Delta\theta \bar{q}_2(\nu_1)$. This rent depends on the contract chosen in the first period since $\nu_1 = \{\underline{\nu}_1, \bar{\nu}_1\}$. Therefore, the first-period incentive and participation constraints are:

$$U(\underline{\theta}, \underline{q}_1, \underline{T}_1, p_1) + \delta \Delta\theta \bar{q}_2(\nu_1) \geq 0 \quad (\underline{PC})$$

$$U(\bar{\theta}, \bar{q}_1, \bar{T}_1, p_1) \geq 0 \quad (\overline{PC})$$

$$U(\underline{\theta}, \underline{q}_1, \underline{T}_1, p_1) + \delta \Delta\theta \bar{q}_2(\nu_1) \geq U(\underline{\theta}, \bar{q}_1, \bar{T}_1, p_1) + \delta \Delta\theta \bar{q}_2(\bar{\nu}_1) \quad (\underline{IC})$$

$$U(\bar{\theta}, \bar{q}_1, \bar{T}_1, p_1) \geq U(\bar{\theta}, \underline{q}_1, \underline{T}_1, p_1) \quad (\overline{IC})$$

The stock constraints are:

$$\underline{q}_1 + \underline{q}_2(\nu_1) \leq S \quad (SC_1)$$

$$\bar{q}_1 + \bar{q}_2(\bar{\nu}_1) \leq S \quad (SC_2)$$

$$\bar{q}_1 + \underline{q}_2(\bar{\nu}_1) \leq S \quad (SC_3)$$

$$\underline{q}_1 + \bar{q}_2(\underline{\nu}_1) \leq S \quad (SC_4)$$

Depending on the binding constraints different cases occur. (\overline{PC}) and (\underline{IC}) always bind; if not, the regulator could increase its revenue and the other constraints remain satisfied. From (\underline{IC}) and (\overline{PC}) binding, (\underline{PC}) is always satisfied.

First, I study the standard case in which only (\underline{IC}) binds. However, if when (\underline{IC}) binds, (\overline{IC}) is not satisfied, then both incentive constraints must bind at equilibrium. Thus, I consider a second case where both incentive constraints bind (countervailing incentives).

4.1 Only the efficient firm's incentive constraint binds

For the moment, I assume that an inefficient firm chooses the contract designed for its type. Hence, I consider that $y = 0$ which implies that $\underline{\nu}_1 = 1$. At the end of this subsection, I define the conditions under which an inefficient firm reveals its type. On the opposite side, an efficient firm is indifferent to the two contracts, it chooses the contract designed for its type $(\underline{T}_1, \underline{q}_1)$ with probability x and the contract designed for an inefficient type (\bar{T}_1, \bar{q}_1) with probability $(1 - x)$. The separation level x allows the regulator to trade off between the two periods. By separating firms during the first period (increase in x), the regulator is more likely to offer the contract $(\underline{T}_1, \underline{q}_1)$ and thus, it is more willing to reduce the informational rent during the first period. As the separation level increases, the expected tax revenue related to the first period increases as well. Nevertheless, by increasing the speed of information revelation, the regulator increases the impact of ratcheting. Indeed, if an efficient firm reveals its type, it must be compensated for the foregone informational rents. Hence, separation increases the informational rent related to the second period, but allows the regulator to correct the inefficient firm's second-period production distortion. Nevertheless, separation decreases the expected tax revenue related to the second period.

The transfers are given by the binding constraints ([PC](#)) and ([IC](#)). Therefore:

$$\underline{T}_1^{NC} = \underline{T}_1^{FB} - \Delta \theta (\bar{q}_1 + \delta \bar{q}_2(\bar{\nu}_1)) \quad (9)$$

$$\bar{T}_1^{NC} = \bar{T}_1^{FB} \quad (10)$$

An efficient firm receives an informational rent $\Delta \theta (\bar{q}_1 + \delta \bar{q}_2(\bar{\nu}_1))$. If it reveals its type, this rent is given in the first period as an upfront payment. If it lies, it receives $\Delta \theta \bar{q}_1$ in the first period and $\Delta \theta \bar{q}_2(\bar{\nu}_1)$ in the second period.

The regulator chooses the first-period extraction and the level of separation to maximize the discounted expected tax revenue under the stock constraints and the inefficient firm's incentive constraint. The regulator's payoff ([11](#)) is obtained by replacing $y = 0$ and the transfers given by ([9](#)) and ([10](#)) in ([8](#)). Hence, the regulator's problem becomes:

$$\max_{\{q_1, \bar{q}_1, x\}} U_R^{NC} = \nu_0 x \left(\underline{T}_1^{FB} - \Delta \theta (\bar{q}_1 + \delta \bar{q}_2(\bar{\nu}_1)) + \delta \underline{T}_2^{FB}(\underline{\nu}_1) \right) + (1 - \nu_0 x) \bar{T}_1^{FB} \quad (11)$$

$$+ \delta \nu_0 (1 - x) \left(\underline{T}_2^{FB}(\bar{\nu}_1) - \Delta \theta \bar{q}_2(\bar{\nu}_1) \right) + \delta (1 - \nu_0) \bar{T}_2^{FB}$$

subject to ([IC](#)), ([SC](#)₁), ([SC](#)₂), ([SC](#)₃)

$$\frac{\partial U_R^{NC}}{\partial \underline{q}_1} = \nu_0 x \left(\frac{\partial \underline{T}_1^{FB}}{\partial \underline{q}_1} + \delta \frac{\partial \underline{T}_2^{FB}(\underline{\nu}_1)}{\partial \underline{q}_1} \right) \quad (12)$$

$$\begin{aligned} \frac{\partial U_R^{NC}}{\partial \bar{q}_1} = & -\nu_0 x \Delta \theta (1 - \delta) + (1 - \nu_0 x) \frac{\partial \bar{T}_1^{FB}}{\partial \bar{q}_1} + \delta \nu_0 (1 - x) \left(\frac{\partial \underline{T}_2^{FB}(\bar{\nu}_1)}{\partial \bar{q}_1} + \Delta \theta \right) \\ & + \delta (1 - \nu_0) \frac{\partial \bar{T}_2^{FB}}{\partial \bar{q}_1} \end{aligned} \quad (13)$$

By solving these first-order conditions, I show in appendix [B.1](#), that in the first period, an efficient firm produces the first best, while an inefficient firm produces at least the same as with commitment (the same if $x = 1$). From the envelope theorem, the optimal separation level x^* has no effect on the inefficient firm's first-period production, and on the second-period production

since the stock is exhausted.⁴ Therefore:

$$\frac{\partial U_R^{NC}}{\partial x} = \nu_0 \left(\underline{T}_1^{FB} - \bar{T}_1^{FB} - \Delta \theta \bar{q}_1 + \delta \underline{T}_2^{FB}(\underline{\nu}_1) - \delta \underline{T}_2^{FB}(\bar{\nu}_1) \right) \quad (14)$$

Since (14) is strictly positive, $x^* = 1$, full-separating contracts are implemented and the inefficient firm's production is the same as under full commitment. To summarize:

Proposition 2 *Under asymmetric information without commitment, if the discount factor is relatively low, there is no countervailing incentive, and*

1. *during the first period, full-separating contracts are implemented and in the second period, the first-best contracts are implemented.*
2. *The extraction path and the discounted expected tax revenue are the same as with commitment.*

In a standard dynamic principal-agent model, a regulator that is unable to commit to long-term contracts faces a trade-off. Separating firms in the first period increases the tax revenue related to the first period, but decreases the tax revenue related to the second period. In the extreme case, that is full separation, in the first period an inefficient firm produces the full-commitment quantity, and the informational rent related to the first period is minimized. In contrast, in the second period, an inefficient firm produces the first best and the informational rent related to this period is maximized. Nevertheless, if the stock is exhausted, separation occurs without costs since the inefficient firm's second-period extraction does not depend on the separation level. As a result, it is optimal for the regulator to fully separate firms, and the outcome is the same with and without commitment.⁵

Proposition 2 shows how the exhaustion of the resource modifies the effect of commitment. Indeed, if the stock is not exhausted, and if there is no countervailing incentive, under full separation the expected tax revenue related to the first period is the same with and without commitment,

⁴When the stock is not exhausted, the separation level does not affect the inefficient firm's first-period production, but it affects the second-period production.

⁵This result does not depend on $\delta < 1$. Even if $\delta > 1$, it is still optimal to fully separate firms.

but that related to the second period is lower without commitment.⁶

I now check under which conditions (\overline{IC}) is satisfied at the equilibrium. An inefficient firm reveals its type only if the cost of lying exceeds the gains:

$$\Delta\theta \underline{q}_1^{FB} \geq \Delta\theta (\overline{q}_1^{FC} + \delta \overline{q}_2^{FB}) \Leftrightarrow \underline{q}_1^{FB} \geq \overline{q}_1^{FC} + \delta \overline{q}_2^{FB} \quad (15)$$

When an inefficient firm misrepresents its type, in the first period, it overproduces and bears the costs $\Delta\theta \underline{q}_1^{FB}$ but captures the informational rent: $\Delta\theta (\overline{q}_1^{FC} + \delta \overline{q}_2^{FB})$. During the second period, only the efficient firm's first-best contract is proposed. Hence, an inefficient firm prefers to leave the relationship rather than bear the overproduction costs $\Delta\theta \underline{q}_2^{FB}$, this is the take-the-money-and-run strategy. The incentive constraint is more stringent than with commitment: $\underline{q}_1^{FB} + \delta \underline{q}_2^{FB} > \overline{q}_1^{FC} + \delta \overline{q}_2^{FC}$, the latter always being satisfied. The following proposition defines the conditions under which the contracts previously defined cannot be implemented (Appendix B.1):

Proposition 3 *In the first period, an inefficient firm understates its costs when the second-period price and discount factor are high, and when the probability of facing an efficient firm and the information asymmetry are low.*

An inefficient firm understates its costs when the informational rent related to the second period is significant, that is when the discount factor and the second-period price are high. It also misrepresents its type when the probability of facing an efficient firm is low, since in this case, the trade-off between informational rent and productive efficiency induces a relatively high informational rent. Finally, the size of the information asymmetry increases both the informational rent and the costs of lying. Nevertheless, an inefficient firm has a greater incentive to lie when the information asymmetry is low.

From (15), it is clear that as the number of contracting periods increases, the inefficient firm's incentive constraint is less likely to be satisfied. Indeed, the upfront payment increases with the

⁶If the stock is not exhausted, semi-separating contracts are only implemented if $\delta > 1$ (necessary but not sufficient condition). If $\delta < 1$, full-separating contracts are implemented and the tax revenue is lower without commitment than with commitment.

number of contracting periods, while the cost of lying stays constant ($\Delta\theta \underline{q}_1^{FB}$).

If when (IC) binds, (\overline{IC}) is not satisfied, then both firms' incentive constraints must bind at the equilibrium.

4.2 Both incentive constraints bind

An efficient firm chooses the contract designed for its type with probability x and an inefficient firm chooses the contract designed for its type with probability $(1 - y)$. If (\overline{PC}) binds, $\overline{T}_1^{NC} = \overline{T}_1^{FB}$, and (IC) binding implies that:

$$\underline{T}_1^{NC} = \underline{T}_1^{FB} - \Delta\theta (\bar{q}_1 + \delta \bar{q}_2(\bar{\nu}_1) - \delta \bar{q}_2(\nu_1)) \quad (16)$$

From (16) and (\overline{PC}) binding, the efficient firm's informational rent is $\Delta\theta (\bar{q}_1 + \delta \bar{q}_2(\bar{\nu}_1))$. From (\overline{PC}) binding, an inefficient firm receives no rent when it reveals its type, and since (\overline{IC}) binds, an inefficient firm must also receive no rent when it lies. Therefore:

$$\Delta\theta \underline{q}_1 = \Delta\theta (\bar{q}_1 + \delta \bar{q}_2(\bar{\nu}_1) - \delta \bar{q}_2(\nu_1)) \Leftrightarrow \underline{q}_1 = \bar{q}_1 + \delta \underbrace{(\bar{q}_2(\bar{\nu}_1) - \bar{q}_2(\nu_1))}_{\geq 0} \quad (17)$$

The left-hand side represents the costs of lying (overproduction), while the right-hand side represents the gains from lying (informational rent). When both incentive constraints bind, the first-period production of an efficient firm and an inefficient firm are positively correlated. If the inefficient firm's production increases, the informational rent increases and, to compensate, the cost of lying must increase as well (increase in the efficient firm's production).

Semi-separating contracts are never optimal.⁷ The regulator proposes full-separating contracts if the discount factor is below a threshold, and above this threshold, a pooling contract is proposed.

⁷Under semi-separating contracts where an inefficient firm randomizes ($x = 1$ and $y > 0$), (17) becomes $\underline{q}_1 = \bar{q}_1 + \delta (S - \bar{q}_1(\bar{\nu}_1) - \delta (S - \bar{q}_1(\nu_1))) \Leftrightarrow \underline{q}_1 = \bar{q}_1$. These semi-separating contracts are equivalent to a pooling contract. The semi-separating contracts where $\underline{\theta}$ randomizes ($x > 0$ and $y = 0$) are also never optimal.

If the discount factor is relatively large, large enough to induce countervailing incentives, but low enough for full-separating contracts to be implemented, $\bar{q}_2(\nu_1) = 0$ and (17) becomes:

$$\underline{q}_1 = \bar{q}_1 + \delta(S - \bar{q}_1) \quad (18)$$

Under full separation, since (15) is violated and (18) holds, if in the first period an efficient firm produces the first best, then an inefficient firm produces a lower quantity than the first best at this period. Similarly, if during the first period an inefficient firm produces the first best, then an efficient firm produces a higher quantity than the first best at this period.⁸ Thus, the correlation with the first-period extractions tends to increase the efficient firm's production above the first best, and to decrease the inefficient firm's production below the first best.

If both (IC) bind, under full separation, the regulator's problem is the following:

$$\begin{aligned} \max_{\underline{q}_1} U_R^{NC} &= \nu_0 \left(\underline{T}_1^{FB} - \Delta\theta \underline{q}_1 + \delta \underline{T}_2^{FB} \right) + (1 - \nu_0) \left(\bar{T}_1^{FB} + \delta \bar{T}_2^{FB} \right) \text{ subject to (18)} \\ \frac{\partial U_R^{NC}}{\partial \bar{q}_1} &= \nu_0 \left(\frac{\partial \underline{T}_1^{FB}}{\partial \underline{q}_1} - \Delta\theta + \delta \frac{\partial \underline{T}_2^{FB}}{\partial \underline{q}_1} \right) \frac{\partial \underline{q}_1}{\partial \bar{q}_1} + (1 - \nu_0) \left(\frac{\partial \bar{T}_1^{FB}}{\partial \bar{q}_1} + \delta \frac{\partial \bar{T}_2^{FB}}{\partial \bar{q}_1} \right) = 0 \end{aligned} \quad (19)$$

By solving (19) and by using (18), the first-period extractions are given by (Appendix B.2):

$$\underline{q}_1^{NC} = \underline{q}_1^{FB} + \frac{(1 - \nu_0)}{1 - (2 - \delta) \delta \nu_0} \left(\bar{q}_1^{FC} + \delta(S - \bar{q}_1^{FC}) - \underline{q}_1^{FB} \right) \quad (20)$$

$$\bar{q}_1^{NC} = \bar{q}_1^{FC} - \frac{(1 - \delta) \nu_0}{1 - (2 - \delta) \delta \nu_0} \left(\bar{q}_1^{FC} + \delta(S - \bar{q}_1^{FC}) - \underline{q}_1^{FB} \right) \quad (21)$$

Since full separating-contracts where only (IC) binds are not incentive-compatible, (15) is violated and $\bar{q}_1^{FC} + \delta(S - \bar{q}_1^{FC}) > \underline{q}_1^{FB}$. During the first period, an efficient firm produces more than the first best to deter an inefficient firm from lying. On the one hand, the regulator increases the efficient firm's production so that the inefficient firm's production is not too low. On the other

⁸Proof: (15) violated, implies: $\underline{q}_1^{FB} < \bar{q}_1^{FC} + \delta(S - \bar{q}_1^{FC}) \Leftrightarrow \underline{q}_1^{FB} < \bar{q}_1^{FB} + \delta(S - \bar{q}_1^{FB})$.
(18)_{| $\underline{q}_1 = \underline{q}_1^{FB}$} implies: $\underline{q}_1^{FB} = \bar{q}_1 + \delta(S - \bar{q}_1)$, and from (15) violated, this implies $\bar{q}_1 < \bar{q}_1^{FB}$.
(18)_{| $\bar{q}_1 = \bar{q}_1^{FB}$} implies: $\underline{q}_1 = \bar{q}_1^{FB} + \delta(S - \bar{q}_1^{FB})$, and from (15) violated, this implies $\underline{q}_1 > \underline{q}_1^{FB}$.

hand, the regulator is willing to decrease the efficient firm's production in order to decrease the informational rent. Using the same argument, the regulator decreases the inefficient firm's production to lower the informational rent and maintain the efficient firm's production relatively close to the first-best level. As a result, in the first period, an inefficient firm produces less than under full commitment and thus less than under symmetric information.

The discount factor affects the first-period extraction through three effects: a countervailing, a resource, and an adverse selection effects.

The first effect is related to countervailing incentives and the induced correlation between the firms' productions. From (18), as previously explained, if the efficient firm's first-period production is set to the first best, the inefficient firm's first-period production is lower than the first best, especially when the discount factor is high. As a result, as the discount factor increases, the efficient firm's first-period production must be further increased. Using the same argument, as the discount factor increases, the inefficient firm's first-period production must be further reduced to avoid a significant upward distortion from an efficient firm.

The second effect is standard in the literature on exhaustible resource. A trade-off takes place between extracting in the first period or in the second period. As the discount factor increases, it is optimal to postpone extraction, and the first-period extraction decreases. This is a direct implication of Hotelling's rule.

The third effect is due to adverse selection, but it is also related to the exhaustion of the resource. As the discount factor increases, the informational rent given in the second period becomes more costly and to compensate, the regulator decreases the inefficient firm's second-period extraction, which automatically increases the first-period extraction.

As the discount factor increases, the countervailing effect increases the efficient firm's first-period extraction, while the resource effect decreases the extraction. For an inefficient firm, as the discount factor increases, the resource and the countervailing effects induce a decrease in production, while the adverse selection effect increases the production. As a result, Hotelling's rule may not hold.

Proposition 4 *Under asymmetric information without commitment, if the discount factor is relatively large, then there is a countervailing incentive and in the first period, full-separating contracts are implemented,*

1. *an efficient firm produces more than under symmetric information, while an inefficient firm produces less than under full commitment.*
2. *an increase in the discount factor may accelerate the firm's extraction which contradicts Hotelling's rule.*

To put the results of Proposition 4 in perspective, I now consider the case in which there is no commitment and the efficiency parameter is not correlated over time.⁹ Under this situation, the revelation of the firm's type in one period does not jeopardize future informational rents. If the types are not correlated over time, when the stock is exhausted, during the first period an efficient firm always produces more than the first best. Thus, whether the cost parameters are correlated or not, an efficient firm may produce more than with symmetric information during the first period. Nevertheless, the intuition behind this overproduction is different in the two settings.

If the efficiency parameter is not correlated over time, then the efficient firm's first-period overproduction comes from future potential production distortions. Indeed, if during one period, a firm is inefficient, due to the trade-off between informational rent and productive efficiency, then it produces less than the first best during this period. Thus, future informational rents decrease the opportunity cost of extracting during the first period. This induces an increase in the efficient firm's first-period production.

With perfectly correlated types, the efficient firm's overproduction aims to prevent an inefficient firm from understating its costs. This overproduction results from the ratchet effect, and only occurs when the discount factor is relatively high, that is, when a countervailing incentive exists and full-separating contracts are proposed. Hence, if the discount factor is relatively low, the most efficient firm produces the first best, while with uncorrelated types, it always produces

⁹This can be viewed as a simplified version of Gaudet et al. (1995) where only two types are considered. This case is defined in appendix F.

more than the first best.

So far, I have assumed that the resource is worthless after the second period, and that it is always optimal to exhaust the stock in the second period. In other words, I have assumed that it is optimal to implement two-period contracts under symmetric and asymmetric information with and without commitment. However, asymmetric information may affect the optimal contract duration, and it may delay or advance the exhaustion of the resource.¹⁰ Under asymmetric information without commitment, when the discount factor is relatively large, a countervailing incentive exists, and during the first period full separating-contracts are implemented. An efficient firm produces more than the first best, which implies that the inability to commit may shorten the contract duration as compared to the first best. On the opposite, since an inefficient produces in the first period less than under full commitment, the inability to commit may extend the contract duration as compared to the first best and to the full commitment. Proposition 4 implies that (Appendix D):

Corollary 1 *Under asymmetric information without commitment, if the discount factor is relatively large, then there is a countervailing incentive and in the first period, full-separating contracts are implemented. If so, the efficient firm's contract duration may be shorter than under symmetric information. The inefficient firm's contract duration may be longer than under full commitment.*

Similarly to the case where the efficiency parameter is not correlated over time, asymmetric information without commitment may shorten the efficient firm's contract duration as compared to the first best. Indeed, during the first period, it is optimal to increase the efficient firm's production to deter an inefficient firm from lying. On the opposite, as compared to the full-commitment case, the inefficient firm's contract duration may be longer. Indeed, it is optimal to further decrease the inefficient firm's first-period production to take into account the correlation between firm's first-period productions.

If the discount factor is high, then the regulator proposes a pooling contract during the first period. It maximizes the expected discounted tax revenue under the constraint that both firms

¹⁰To study how the inability to commit affects contract duration, I introduce the possibility for firms to exhaust the stock in a third period, and I assume that the resource is worthless after this period (appendix C).

participate. At equilibrium, the inefficient firm's participation constraint binds and the transfer is given by: $T_1 = \bar{T}_1^{FB}$. The problem is the following:

$$\max_{q_1} U_R^P = \bar{T}_1^{FB} + \delta \left(\nu_0 \left(\bar{T}_2^{FB} - \Delta \theta (S - q_1) \right) + (1 - \nu_0) \bar{T}_2^{FB} \right) \quad (22)$$

$$\frac{\partial U_R^P}{\partial q_1} = \frac{\partial \bar{T}_1^{FB}}{\partial q_1} + \delta \left(\nu_0 \left(\frac{\partial \bar{T}_2^{FB}}{\partial q_1} + \Delta \theta \right) + (1 - \nu_0) \frac{\partial \bar{T}_2^{FB}}{\partial q_1} \right) = 0 \quad (23)$$

From (23), the following proposition is deduced:

Proposition 5 *Under asymmetric information without commitment, if the discount factor is large, then a countervailing incentive exists, and in the first period, a pooling contract is implemented. Both firms produce the inefficient firm's first-best level.*

In the first period, under a pooling contract, an efficient firm produces a lower quantity than the first best and in the second period, a larger quantity than the first best. On the opposite an inefficient produces at each period the same as under symmetric information. In appendix B.2, I define the discount factor above which, a pooling contract is implemented. A direct consequence of Proposition 5 is that (Appendix D):

Corollary 2 *Under asymmetric information without commitment, if the discount factor is large, then a countervailing incentive exists, and in the first period, a pooling contract is implemented. The efficient firm's contract duration may be longer than under symmetric information, while the inefficient firm's contract duration is the same.*

To highlight the effect of the exhaustion of the resource, I now discuss the case in which the stock is not exhausted, and there is a countervailing incentive. For relatively low discount factors, full-separating contracts are implemented, while for higher discount factors, semi-separating contracts whereby an inefficient firm randomizes are optimal. In the first period, as compared to the first best, an efficient firm produces more under full separation and less under semi separation. An inefficient firm always produces less than the first best. Under full separation, the discount factor only affects the first-period extraction through the countervailing incentive effect. As a result, in contrast to proposition 4, an increase in the discount factor increases the efficient firm's first-period extraction, while it decreases the inefficient one.

5 Conclusion

This paper has shown that when the discount factor is low, the tax revenue and the extraction path are the same with and without commitment, and thus the inability to commit is costless. However, this result is related to the assumption that the stock is exhausted during the second period. If the terminal period is greater than two periods, then separating firms at the period before exhaustion is always optimal and costless. Nevertheless, in the previous periods, the inability to commit is costly. Hence, the exhaustion of the resource decreases the cost of non-commitment and this cost is null in a two-period model.¹¹

This paper has put particular emphasis on the discount factor and how it affects the type of contracts implemented and the extraction path (overview table in appendix G). This study shows that if the regulator is unable to commit, then an increase in the discount factor may accelerate the extraction, which contradicts Hotelling's rule. Indeed, as the discount factor increases, the second-period informational rent increases, and to compensate the regulator increases the efficient firm's first-period production, and decreases the inefficient firm's second-period production. As the previous studies on the topic, this paper finds that the most efficient firm may produce more than the first best. With uncorrelated types, this overproduction comes from the fact that the second-period informational rent decreases the opportunity cost of extracting during the first period. On the opposite side, in the present paper, this overproduction results from the ratchet effect and aims to prevent an inefficient firm from lying. Hence, this overproduction only appears when a countervailing incentive exists. I also find that without commitment, asymmetric information has an ambiguous effect on the efficient firm's optimal contract duration. Indeed, when the discount factor is low, as compared to the first best, the inability to commit has no effect, when the discount factor is relatively large, it may shorten the efficient firm's contract duration, while when it is large, it may extend the contract duration. This result contrasts with the case in which types are uncorrelated over time, and where asymmetric information tends to shorten the efficient firm's contract duration.

¹¹To illustrate this point, I define in appendix C the second-best contracts when the stock is exhausted during the third period and when only (*IC*) binds.

Contrary to [Gaudet et al. \(1995\)](#), [Osmundsen \(1998\)](#) and [Hung et al. \(2006\)](#), this paper only considers two types of firm. However, with a continuum of types, without commitment, full-separating contracts are usually not optimal, and a pooling contract is implemented. Under a pooling contract in the first period, the most efficient firm produces less than the first best. This paper also relies on the assumption that the cost parameter is perfectly correlated over time, and thus it considers an extreme ratchet effect. Indeed, if the regulator learns the firm's type in the first period, it is fully informed in the second period and captures all of the revenue. However, a more realistic assumption is to consider imperfectly correlated costs.

As a continuation to this work, it would be interesting to define the optimal renegotiation proof contracts. The renegotiation proof outcome usually lies between the outcome of full and non commitment.

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Appendices

Let us denote $X_t = p_t - \theta$; $\underline{X}_t = p_t - \underline{\theta}$; $\overline{X}_t = p_t - \overline{\theta}$; $V(\theta, q_1, q_2) = U(\theta, q_1, 0, p_1) + \delta U(\theta, q_2, 0, p_2)$.

A Benchmarks:

Symmetric information:

$$\max_{\{q_1, T_1, q_2, T_2\}} U_R^{FB} = T_1 + \delta T_2 \text{ subject to} \quad (24)$$

$$U(\theta, q_1, T_1, p_1) + \delta U(\theta, q_2, T_2, p_2) \geq 0 \quad (25)$$

$$q_1 + q_2 \leq S \quad (26)$$

Since (24) increases with T_t and (25) decreases with T_t , at equilibrium (25) binds, and $T_1 + \delta T_2 = T_1^{FB} + \delta T_2^{FB}$ given by (5). The problem becomes: $\max_{\{q_1, q_2\}} U_R^{FB} = T_1^{FB} + \delta T_2^{FB}$ subject to (26).

If (26) is slack: $\frac{\partial U_R^{FB}}{\partial q_t} = \delta^{t-1} (X_t - b q_t) = 0$ and $q_t^{FB} = \frac{X_t}{b}$.

If (26) binds: $\frac{\partial U_R^{FB}}{\partial q_1} = X_1 - b q_1 - \delta (X_2 - b (S - q_1)) = 0$, and:

$$q_1^{FB} = \frac{X_1 - \delta X_2 + \delta b S}{b(1 + \delta)} \quad (27)$$

(26) binds if: $\frac{X_1}{b} + \frac{X_2}{b} > S \Leftrightarrow bS - X_2 - X_1 < 0$ and $\frac{\partial q_1^{FB}}{\partial \delta} = \frac{bS - X_2 - X_1}{b(1 + \delta)^2} < 0$.

Asymmetric information and full commitment:

$$\max_{\{\underline{q}_1, \underline{T}_1, \underline{q}_2, \underline{T}_2, \bar{q}_1, \bar{T}_1, \bar{q}_2, \bar{T}_2\}} U_R^{FC} = \nu_0 (\underline{T}_1 + \delta \underline{T}_2) + (1 - \nu_0) (\bar{T}_1 + \delta \bar{T}_2) \text{ subject to} \quad (28)$$

$$U(\underline{\theta}, \underline{q}_1, \underline{T}_1, p_1) + \delta U(\underline{\theta}, \underline{q}_2, \underline{T}_2, p_2) \geq 0 \quad (29)$$

$$U(\bar{\theta}, \bar{q}_1, \bar{T}_1, p_1) + \delta U(\bar{\theta}, \bar{q}_2, \bar{T}_2, p_2) \geq 0 \quad (30)$$

$$U(\underline{\theta}, \underline{q}_1, \underline{T}_1, p_1) + \delta U(\underline{\theta}, \underline{q}_2, \underline{T}_2, p_2) \geq U(\underline{\theta}, \bar{q}_1, \bar{T}_1, p_1) + \delta U(\underline{\theta}, \bar{q}_2, \bar{T}_2, p_2) \quad (31)$$

$$U(\bar{\theta}, \bar{q}_1, \bar{T}_1, p_1) + \delta U(\bar{\theta}, \bar{q}_2, \bar{T}_2, p_2) \geq U(\bar{\theta}, \underline{q}_1, \underline{T}_1, p_1) + \delta U(\bar{\theta}, \underline{q}_2, \underline{T}_2, p_2) \quad (32)$$

$$\underline{q}_1 + \underline{q}_2 \leq S \quad (33)$$

$$\bar{q}_1 + \bar{q}_2 \leq S \quad (34)$$

At equilibrium (30) and (31) bind. From (30) binding, $\bar{T}_1^{FC} + \delta \bar{T}_2^{FC} = \bar{T}_1^{FB} + \delta \bar{T}_2^{FB}$, and (31) binding becomes: $\underline{T}_1^{FB} - \underline{T}_1^{FC} + \delta (\underline{T}_2^{FB} - \underline{T}_2^{FC}) = C(\bar{\theta}, \bar{q}_1) - C(\underline{\theta}, \bar{q}_1) + \delta (C(\bar{\theta}, \bar{q}_2) - C(\underline{\theta}, \bar{q}_2))$.

The efficient firm's transfers are then: $\underline{T}_1^{FC} + \delta \underline{T}_2^{FC} = \underline{T}_1^{FB} + \delta \underline{T}_2^{FB} - \Delta \theta (\bar{q}_1 + \delta \bar{q}_2)$. To make the comparison easier with the case of non commitment, I assume that the transfers are decomposed as in (6) and (7). Using (6) and (7), the non-binding constraint (29) becomes: $\Delta \theta (\bar{q}_1 + \delta \bar{q}_2) \geq 0$ and is always satisfied, while (32) becomes: $-\Delta \theta (\underline{q}_1 - \bar{q}_1 + \delta (\underline{q}_2 - \bar{q}_2)) \leq 0$. Replacing the transfers in (28) gives:

$$\max_{\{\underline{q}_1, \bar{q}_1, \underline{q}_2, \bar{q}_2\}} U_R^{FC} = \nu_0 (\underline{T}_1^{FB} - \Delta \theta \bar{q}_1 + \delta (\underline{T}_2^{FB} - \Delta \theta \bar{q}_2)) + (1 - \nu_0) (\bar{T}_1^{FB} + \delta \bar{T}_2^{FB}) \quad (35)$$

subject to (32), (33), (34)

By differentiating (35) with respect to \underline{q}_1 and \underline{q}_2 , $q_t^{FC} = q_t^{FB}$.

If (34) is slack: $\frac{\partial U_R^{FC}}{\partial \bar{q}_t} = \delta^{t-1} (-\nu_0 \Delta \theta + (1 - \nu_0) (\bar{X}_t - b \bar{q}_t)) = 0$, and $\bar{q}_t^{FC} = \frac{\bar{X}_t}{b} - \frac{\Delta \theta \nu_0}{b(1 - \nu_0)}$.

If (34) binds: $\frac{\partial U_R^{FC}}{\partial \bar{q}_1} = (1 - \nu_0) (\bar{X}_1 - b \bar{q}_1 - \delta (\bar{X}_2 - b(S - \bar{q}_1))) - \nu_0 \Delta \theta (1 - \delta) = 0$, and

$$\bar{q}_1^{FC} = \bar{q}_1^{FB} - \frac{\Delta \theta \nu_0 (1 - \delta)}{b(1 - \nu_0)(1 + \delta)} \quad (36)$$

Regardless of (34) binding, (32) is always satisfied. (34) binds if: $\sum_{t=1}^{t=2} \left(\frac{\bar{X}_t}{b} - \frac{\Delta\theta\nu_0}{b(1-\nu_0)} \right) > S \Leftrightarrow 2\nu_0\Delta\theta + (1-\nu_0)(bS - \bar{X}_1 - \bar{X}_2) < 0$, and $\frac{\partial \bar{q}_1^{FC}}{\partial \delta} = \frac{2\nu_0\Delta\theta + (1-\nu_0)(bS - \bar{X}_1 - \bar{X}_2)}{b(1+\delta)^2(1-\nu_0)} < 0$.

The cost of the informational rent is: $C_{IR} = \nu_0\Delta\theta(\bar{q}_1^{FC} + \delta(S - \bar{q}_1^{FC}))$, and the production distortion cost is: $C_{PD}^{FC} = (1-\nu_0)(V(\bar{\theta}, \bar{q}_1^{FB}, S - \bar{q}_1^{FB}) - V(\bar{\theta}, \bar{q}_1^{FC}, S - \bar{q}_1^{FC}))$, which is equal to:

$$\begin{aligned} & (1-\nu_0) \left((\bar{q}_1^{FB} - \bar{q}_1^{FC}) \left(\bar{X}_1 - \frac{b}{2}(\bar{q}_1^{FB} + \bar{q}_1^{FC}) \right) + \delta(\bar{q}_1^{FC} - \bar{q}_1^{FB}) \left(\bar{X}_2 - bS + \frac{b}{2}(\bar{q}_1^{FB} + \bar{q}_1^{FC}) \right) \right) \\ &= (1-\nu_0)(1+\delta) \frac{b}{2}(\bar{q}_1^{FB} - \bar{q}_1^{FC})^2 = \frac{(1-\delta)^2\nu_0^2\Delta\theta^2}{2b(1+\delta)(1-\nu_0)} \end{aligned}$$

When the stock is not exhausted $C_{PD}^{FC} = \frac{(1+\delta)\nu_0^2\Delta\theta^2}{2b(1-\nu_0)}$ is larger than when the stock is exhausted.

B Asymmetric information without commitment

During the second period, for a given stock $S_2 = S - q_1$ and updated belief ν_1 , the regulator solves:

$$\begin{aligned} & \max_{\{q_2, \underline{T}_2, \bar{q}_2, \bar{T}_2\}} U_{R_2}^{NC} = \nu_1 \underline{T}_2 + (1-\nu_1) \bar{T}_2 \text{ subject to} \\ & U(\underline{\theta}, q_2, \underline{T}_2, p_2) \geq 0; U(\bar{\theta}, \bar{q}_2, \bar{T}_2, p_2) \geq 0; U(\underline{\theta}, q_2, \underline{T}_2, p_2) \geq U(\underline{\theta}, \bar{q}_2, \bar{T}_2, p_2); \\ & U(\bar{\theta}, \bar{q}_2, \bar{T}_2, p_2) \geq U(\bar{\theta}, q_2, \underline{T}_2, p_2); q_2 \leq S_2; \bar{q}_2 \leq S_2 \end{aligned}$$

At equilibrium, \overline{PC}_2 and \underline{IC}_2 bind. From \overline{PC}_2 binding, $\bar{T}_2^{NC} = \bar{T}_2^{FB}$, and \underline{IC}_2 binding implies $\underline{T}_2^{NC} = \bar{T}_2^{FB} - \Delta\theta\bar{q}_2$. Using the binding constraints, \underline{PC}_2 becomes $U(\underline{\theta}, q_2, \underline{T}_2, p_2) = \Delta\theta\bar{q}_2(\nu_1) \geq 0$, which is always satisfied, and \overline{IC}_2 becomes $-\Delta\theta(q_2^{FB} - \bar{q}_2^{NC}) \leq 0$.

The problem can be rewritten as: $\max_{\{q_2, \bar{q}_2\}} U_{R_2}^{NC} = \nu_1 (\underline{T}_2^{FB} - \Delta\theta\bar{q}_2) + (1-\nu_1) \bar{T}_2^{FB}$ subject to $\overline{IC}_2, \underline{EC}_2, \overline{EC}_2$. Solving the problem gives $q_t^{NC} = q_t^{FB}$. If \overline{EC}_2 is slack, $\bar{q}_2^{NC} = \bar{q}_2^{FB} - \frac{\Delta\theta\nu_1}{b(1-\nu_1)}$.

\overline{EC}_2 binds if $\frac{\bar{X}_2}{b} - \frac{\Delta\theta\nu_1}{b(1-\nu_1)} > S_2$ and \underline{EC}_2 binds if $\frac{\underline{X}_2}{b} > S_2$. From $\frac{\underline{X}_2}{b} > \frac{\bar{X}_2}{b} - \frac{\Delta\theta\nu_1}{b(1-\nu_1)}$, for a given stock S_2 , it may be optimal for $\underline{\theta}$ to exhaust the stock, while it is not for $\bar{\theta}$.

From $q_2^{FB} > \bar{q}_2^{NC}$, \overline{IC}_2 is always satisfied.

B.1 Only (IC) binds

Proposition 2:

If only (IC) binds, $y = 0$ and $\nu_1 = 1$ and $\bar{q}_2(\nu_1) = 0$. From (PC) binding, $\bar{T}_1^{FC} = \bar{T}_1^{FB}$.

Using $\bar{T}_1^{FC} = \bar{T}_1^{FB}$ and $\bar{q}_2(\nu_1) = 0$, (IC) becomes: $U(\theta, \underline{q}_1, \underline{T}_1, p_1) \geq U(\theta, \bar{q}_1, \bar{T}_1^{FB}, p_1) + \delta \Delta \theta \bar{q}_2(\bar{\nu}_1)$.

If (IC) binds: $\underbrace{p_1 \underline{q}_1 - C(\underline{q}_1, \underline{\theta}) - \underline{T}_1^{NC}}_{=\underline{T}_1^{FB}} = \underbrace{C(\bar{q}_1, \bar{\theta}) - C(\bar{q}_1, \underline{\theta})}_{=\Delta \theta \bar{q}_1} + \delta \Delta \theta \bar{q}_2(\bar{\nu}_1)$ which gives (9).

$$(13) = 0 \Leftrightarrow \frac{\partial U_R^{NC}}{\partial \bar{q}_1} = -\nu_0 x \Delta \theta (1 - \delta) + (1 - \nu_0 x) \left(\bar{X}_1 - b \bar{q}_1 - \delta \left(\bar{X}_2 - b (S - \bar{q}_1) \right) \right) = 0$$

$$\bar{q}_1 = \bar{q}_1^{FB} - \frac{\Delta \theta \nu_0 x (1 - \delta)}{b(1 + \delta)(1 - \nu_0 x)} = \bar{q}_1^{FC} + \frac{(1 - \delta)(1 - x) \Delta \theta \nu_0}{b(1 + \delta)(1 - \nu_0)(1 - \nu_0 x)} \quad (37)$$

$$(14) \Leftrightarrow \frac{\partial U_R^{NC}}{\partial x} = \left(\underline{X}_1 \underline{q}_1^{FB} - \bar{X}_1 \bar{q}_1 - \Delta \theta \bar{q}_1 + \delta \underline{X}_2 \left(S - \underline{q}_1^{FB} - (S - \bar{q}_1^{NC}) \right) \right)$$

$$+ \nu_0 \frac{b}{2} \underbrace{\left(\bar{q}_1^2 - \underline{q}_1^{FB2} + \delta (S - \bar{q}_1)^2 - \delta (S - \underline{q}_1^{FB})^2 \right)}_{=(\underline{q}_1^{FB} - \bar{q}_1) (2\delta S - (1 + \delta)(\underline{q}_1^{FB} + \bar{q}_1))}$$

$$= \nu_0 (\underline{q}_1^{FB} - \bar{q}_1) \underbrace{\left(\underline{X}_1 - \delta \underline{X}_2 + \delta b S \right)}_{=b \underline{q}_1^{FB} (1 + \delta)} - \frac{b}{2} (1 + \delta) (\underline{q}_1^{FB} + \bar{q}_1) = \nu_0 \frac{b}{2} (1 + \delta) (\underline{q}_1^{FB} - \bar{q}_1)^2 > 0$$

Thus $x^* = 1$, and from (37), $\bar{q}_1 = \bar{q}_1^{FC}$. Since the stock is exhausted, $\bar{q}_2 = \bar{q}_2^{FC}$ and $U_R^{NC} = U_R^{FC}$.

Proposition 3:

$$(15) \Leftrightarrow \delta (1 - \nu_0) (\underline{X}_1 - \delta \underline{X}_2 - b S) + (1 - \delta)^2 \Delta \theta \geq 0 \quad (38)$$

Since $\underline{q}_2^{FB} = S - \underline{q}_1^{FB} = \frac{\delta \underline{X}_2 - \underline{X}_1 + b S}{b(1 + \delta)} > 0$, $\underline{X}_1 - \delta \underline{X}_2 - b S < 0$ and $\frac{\partial (38)}{\partial \delta} < 0$. Thus, (38)=0 defines

δ_1 , the threshold below which (IC) is satisfied: $\frac{\partial (38)}{\partial p_2} < 0$, $\frac{\partial (38)}{\partial \underline{\theta}} < 0$, $\frac{\partial (38)}{\partial \bar{\theta}} > 0$, $\frac{\partial (38)}{\partial \nu_0} > 0$, $\frac{\partial (38)}{\partial S} < 0$.

If none of the firms exhaust the stock, (15) is equivalent to: $\delta < \frac{\Delta \theta}{(1 - \nu_0) \bar{X}_2}$.

B.2 Both (*IC*) bind

Proposition 4:

Inserting $\bar{T}_1^{NC} = \bar{T}_1^{FB}$ in (IC) gives: $\underbrace{p_1 \underline{q}_1 - C(\underline{q}_1, \underline{\theta}) - \bar{T}_1^{NC}}_{=\bar{T}_1^{FB}} + \delta \Delta \theta \bar{q}_2(\underline{\nu}_1) \geq \underbrace{C(\bar{q}_1, \bar{\theta}) - C(\bar{q}_1, \underline{\theta})}_{=\Delta \theta \bar{q}_1} + \delta \Delta \theta \bar{q}_2(\bar{\nu}_1),$

which implies (16). Using (16) and $\bar{T}_1^{NC} = \bar{T}_1^{FB}$, (*IC*) binding becomes:

$p_1 \underline{q}_1 - C(\underline{q}_1, \bar{\theta}) - (\bar{T}_1^{FB} - \Delta \theta (\bar{q}_1 + \delta \bar{q}_2(\bar{\nu}_1) - \delta \bar{q}_2(\underline{\nu}_1))) = 0$, which is equivalent to:

$\underbrace{C(\underline{q}_1, \underline{\theta}) - C(\underline{q}_1, \bar{\theta})}_{=-\Delta \theta \underline{q}_1} + \Delta \theta (\bar{q}_1 + \delta \bar{q}_2(\bar{\nu}_1) - \delta \bar{q}_2(\underline{\nu}_1)) = 0$, which implies (17).

$$\bar{q}_2(\bar{\nu}_1) - \bar{q}_2(\underline{\nu}_1) = \frac{\Delta \theta \nu_0 (x-y)}{b(1-y)(1-\nu_0)y} > 0 \Leftrightarrow \underline{q}_1 > \bar{q}_1.$$

$$(19) \Leftrightarrow (\bar{X}_1 - b \bar{q}_1 - \delta (\bar{X}_2 - b(S - \bar{q}_1))) (\nu_0 (1 - \delta) + 1 - \nu_0) - \delta (1 - \delta) \nu_0 (\Delta \theta + b(1 + \delta) (S - \bar{q}_1)) = 0$$

$$\begin{aligned} \Leftrightarrow \bar{q}_1^{NC} &= \bar{q}_1^{FB} - \frac{(1 - \delta) \delta \nu_0 (\Delta \theta + \delta \bar{X}_2 - \bar{X}_1 + bS)}{b(\delta + 1)((\delta - 2)\delta \nu_0 + 1)} \\ &= \bar{q}_1^{FC} + \frac{(1 - \delta) (\delta (\underline{X}_1 - \delta \underline{X}_2 - bS) (1 - \nu_0) + (1 - \delta)^2 \Delta \theta) \nu_0}{b(\delta + 1)((\delta - 2)\delta \nu_0 + 1)} \end{aligned}$$

which can be rewritten as (21). Substituting \bar{q}_1 in (18) gives \underline{q}_1 defined by (20).

Hotelling's rule may not hold, to prove this point I take two examples¹²

If $(b, S, p_1, p_2, \nu_0, \underline{\theta}, \bar{\theta}) = (1, 10, 20, 22, .6, 1, 4)$, full-separating contracts where both (*IC*) bind are offered for $\delta \in [\delta_1, \delta_2]$ where $\delta_1 = \frac{5}{9}$ and $\delta_2 = .6399$. $\frac{\partial \underline{q}_1^{NC}}{\partial \delta} < 0$ for $\delta \in [\frac{5}{9}, .6103]$ and $\frac{\partial \underline{q}_1^{NC}}{\partial \delta} > 0$ for $\delta \in [.6103, .6399]$. $\frac{\partial \bar{q}_1^{NC}}{\partial \delta} < 0$ for $\delta \in [\frac{5}{9}, .6399]$.

If $(b, S, p_1, p_2, \nu_0, \underline{\theta}, \bar{\theta}) = (1, 4, 10, 7, .8, .1, 2)$, full-separating contracts where both (*IC*) bind are offered for $\delta \in [\delta_1, \delta_2]$ where $\delta_1 = \frac{131-3\sqrt{809}}{52} = 0.8783$ and $\delta_2 = .919438$. $\frac{\partial \bar{q}_1^{NC}}{\partial \delta} < 0$ for $\delta \in [0.8783, 0.8885]$, and $\frac{\partial \bar{q}_1^{NC}}{\partial \delta} > 0$ for $\delta \in [0.8885, .919438]$. For $\delta \in [0.8783, .919438]$, $\frac{\partial \underline{q}_1^{NC}}{\partial \delta} < 0$.

¹² δ_2 is the threshold above which a pooling contract is proposed. This threshold is defined in the next paragraph.

Threshold above which a pooling contract is implemented:

$$\begin{aligned}
(23) \Leftrightarrow \bar{X}_1 - b q_1 - \delta \left(\nu_0 (\underline{X}_2 - b(S - q_1) - \Delta \theta) + (1 - \nu_0) (\bar{X}_2 - b(S - q_1)) \right) &= 0 \\
\Leftrightarrow \bar{X}_1 - b q_1 - \delta (\bar{X}_1 - b(S - q_1)) = 0 \Leftrightarrow q_1 = \bar{q}_1^{FB}
\end{aligned}$$

The regulator proposes a pooling contract if the cost of full separation is larger than the cost of full pooling $C^{FS} > C^P$. Using \underline{q}_1^{NC} and \bar{q}_1^{NC} given by (20) and (21):

$$\begin{aligned}
C^{FS} &= \nu_0 \left(V(\underline{\theta}, \underline{q}_1^{FB}, S - \underline{q}_1^{FB}) - V(\underline{\theta}, \underline{q}_1^{NC}, S - \underline{q}_1^{NC}) + \Delta \theta \bar{q}_1^{NC} \right) \\
&\quad + (1 - \nu_0) \left(V(\bar{\theta}, \bar{q}_1^{FB}, S - \bar{q}_1^{FB}) - V(\bar{\theta}, \bar{q}_1^{NC}, S - \bar{q}_1^{NC}) \right) \\
&= \nu_0 \left(\Delta \theta \underline{q}_1^{NC} + \frac{b}{2} (1 + \delta) (\underline{q}_1^{FB} - \underline{q}_1^{NC})^2 \right) + (1 - \nu_0) \frac{b}{2} (1 + \delta) (\bar{q}_1^{FB} - \bar{q}_1^{NC})^2 \\
C^P &= \nu_0 \left(V(\underline{\theta}, \underline{q}_1^{FB}, S - \underline{q}_1^{FB}) - U(\bar{\theta}, \bar{q}_1^{FB}, 0, p_1) - \delta U(\underline{\theta}, S - \bar{q}_1^{FB}, 0, p_2) + \delta \Delta \theta (S - \bar{q}_1^{FB}) \right) \\
&= \nu_0 \Delta \theta (\bar{q}_1^{FB} + \delta (S - \bar{q}_1^{FB})) + \nu_0 \frac{b}{2} (1 + \delta) (\underline{q}_1^{FB} - \bar{q}_1^{FB})^2
\end{aligned}$$

Thus, a pooling contract is implemented if:

$$\begin{aligned}
&\frac{b}{2} (1 + \delta) \left((\underline{q}_1^{FB} - \underline{q}_1^{NC})^2 \nu_0 + (\bar{q}_1^{FB} - \bar{q}_1^{NC})^2 (1 - \nu_0) - (\underline{q}_1^{FB} - \bar{q}_1^{FB})^2 \nu_0 \right) \\
&\quad + \Delta \theta \nu_0 (\underline{q}_1^{NC} - \bar{q}_1^{FB} - \delta (S - \bar{q}_1^{FB})) > 0 \\
\Leftrightarrow &\delta \nu_0 (\underline{X}_1 - \delta \underline{X}_2 - b S) \left(\delta (1 - \nu_0) (\underline{X}_1 - \delta \underline{X}_2 - b S) + (1 - \delta)^2 \Delta \theta \right) \\
&\quad + \delta \nu_0 (1 - \delta)^2 \Delta \theta (\underline{X}_1 - \delta \underline{X}_2 - b S + \Delta \theta (\delta - 2)) > 0
\end{aligned}$$

I define δ_2 such that $C^{FS} = C^P$. For $\delta = 1$, $C^{FS} > C^P$, thus $\delta_2 < 1$. For $\delta = \delta_1$, $C^{FS} < C^P$, indeed, the first term disappears for $\delta = \delta_1$, and the second term is negative from $\underline{q}_2^{FB} > 0$ and $\delta < 1$.

C Three-period model

Let me consider the case in which both firms extract a positive quantity during the first two periods, and then exhaust the stock during the third period. The resource is assumed to be worthless after the third period. The problem is always solved backward. Hence, at the last two periods, the problem is the same as the two-period model except that $X_1 = X_2$, $X_2 = X_3$ and $S = S_2 = S - q_1$.

The first best: All types of firm exhaust the stock during the third period if $\sum_{t=1}^{t=3} \frac{\bar{X}_t}{b} > S$. Using (27), the extractions at the last two periods are:

$$q_2^{FB}(S_2) = \frac{X_2 - \delta X_3 + \delta b S_2}{b(1 + \delta)} \quad (39)$$

$$q_3^{FB}(S_2) = S_2 - q_2^{FB}(S_2) = \frac{\delta X_3 - X_2 + b S_2}{b(1 + \delta)} \quad (40)$$

Note that the stock is exhausted during the second period if $q_3^{FB}(S_2) < 0$, that is if:

$$\delta X_3 - X_2 + b S_2 < 0 \quad (41)$$

Given (39) and (40), the regulator solves in the first period: $\max_{q_1} U_R^{FB} = T_1^{FB} + \delta T_2^{FB} + \delta^2 T_3^{FB}$, which gives:

$$q_1^{FB} = \frac{(1 + \delta) X_1 - \delta^2 (X_2 + X_3 - b S)}{b(1 + \delta + \delta^2)} \quad (42)$$

Full commitment: Both firms exhaust the stock if: $\sum_{t=1}^{t=3} \left(\frac{\bar{X}_t}{b} - \frac{\Delta \theta}{b(1 - \nu_0)} \right) > S$. $\underline{\theta}$ produces the first best, and $\bar{\theta}$ produces:

$$\bar{q}_1^{FC} = \bar{q}_1^{FB} - \frac{(1 - \delta) (2\delta + 1) \Delta \theta \nu_0}{b (\delta^2 + \delta + 1) (1 - \nu_0)} \quad (43)$$

$$\bar{q}_2^{FC} = \frac{\bar{X}_2 - \delta \bar{X}_3 + b \delta \bar{S}_2^{FC}}{b(1 + \delta)} - \frac{(1 - \delta) \nu_0 \Delta \theta}{b(1 + \delta) (1 - \nu_0)} = \bar{q}_2^{FB}(\bar{S}_2^{FB}) - \frac{(1 - \delta)^2 \Delta \theta \nu_0}{b (\delta^2 + \delta + 1) (1 - \nu_0)} \quad (44)$$

$$\bar{q}_3^{FC} = \frac{\delta \bar{X}_3 - \bar{X}_2 + b \bar{S}_2^{FC}}{b(1 + \delta)} + \frac{(1 - \delta) \Delta \theta \nu_0}{b(1 + \delta) (1 - \nu_0)} = \bar{q}_3^{FB}(\bar{S}_2^{FB}) + \frac{(1 - \delta) (\delta + 2) \Delta \theta \nu_0}{b (\delta^2 + \delta + 1) (1 - \nu_0)} \quad (45)$$

No commitment and only (IC) binds: All types of firm exhaust the stock during the third period if: $(1 - \nu_0) (bS - \bar{X}_1 - \bar{X}_2 - \bar{X}_3) + \nu_0 \Delta \theta < 0$.¹³ From the two-period case, in the second period, full separation is optimal, and an efficient firm produces the first best given by (39). From (36), by replacing ν_0 by $\nu_1 = \{\nu_1 = 1, \bar{\nu}_1 = \frac{\nu_0(1-x)}{1-\nu_0 x}\}$, an inefficient firm produces: $\bar{q}_2^{NC} = \bar{q}_2^{FB} - \frac{\Delta \theta \nu_1 (1-\delta)}{b(1-\nu_1)(1+\delta)}$. If only (IC), binds, $\bar{q}_2^{NC}(\nu_1) = 0$, and to simplify, I denote $\bar{q}_2^{NC}(\bar{\nu}_1) = \bar{q}_2^{NC}$. In the first period, the problem regulator's problem is:

$$\begin{aligned}
\max_{\{q_1, \bar{q}_1, x\}} U_R^{NC} &= \nu_0 x \left(\underline{T}_1^{FB} - \Delta \theta (\bar{q}_1 + \delta \bar{q}_2^{NC} + \delta^2 \bar{q}_3^{NC}) + \delta \underline{T}_2^{FB} + \delta^2 \underline{T}_3^{FB} \right) + (1 - \nu_0 x) \bar{T}_1^{FB} \\
&\quad + \delta (1 - \nu_0) \left(\bar{T}_2^{FB} + \delta \bar{T}_3^{FB} \right) + \delta \nu_0 (1 - x) \left(\underline{T}_2^{FB}(\bar{\nu}_1) - \Delta \theta (\bar{q}_2^{NC} + \delta \bar{q}_3^{NC}) + \delta \underline{T}_3^{FB}(\bar{\nu}_1) \right) \\
\frac{\partial U_R^{NC}}{\partial q_1} &= \nu_0 x \left(\frac{\partial \underline{T}_1^{FB}}{\partial q_1} + \delta \frac{\partial \underline{T}_2^{FB}}{\partial q_1} + \delta^2 \frac{\partial \underline{T}_3^{FB}}{\partial q_1} \right) \\
\frac{\partial U_R^{NC}}{\partial \bar{q}_1} &= -\nu_0 x \Delta \theta \left(1 + \delta \frac{\partial \bar{q}_2^{NC}}{\partial \bar{q}_1} + \delta^2 \frac{\partial \bar{q}_3^{NC}}{\partial \bar{q}_1} \right) + (1 - \nu_0 x) \frac{\partial \bar{T}_1^{FB}}{\partial \bar{q}_1} + \delta (1 - \nu_0) \left(\frac{\partial \bar{T}_2^{FB}}{\partial \bar{q}_1} + \delta \frac{\partial \bar{T}_3^{FB}}{\partial \bar{q}_1} \right) \\
&\quad + \delta \nu_0 (1 - x) \left(\frac{\partial \underline{T}_2^{FB}(\bar{\nu}_1)}{\partial \bar{q}_1} + \delta \frac{\partial \underline{T}_3^{FB}(\bar{\nu}_1)}{\partial \bar{q}_1} \right) - \delta \nu_0 (1 - x) \Delta \theta \left(\frac{\partial \bar{q}_2^{NC}}{\partial \bar{q}_1} + \delta \frac{\partial \bar{q}_3^{NC}}{\partial \bar{q}_1} \right) \\
&= -\nu_0 \Delta \theta \left(x + \delta \frac{\partial \bar{q}_2^{NC}}{\partial \bar{q}_1} + \delta^2 \frac{\partial \bar{q}_3^{NC}}{\partial \bar{q}_1} \right) + (1 - \nu_0 x) (\bar{X}_1 - b \bar{q}_1) \\
&\quad + \delta (1 - \nu_0) \left((\bar{X}_2 - b \bar{q}_2^{NC}) \frac{\partial \bar{q}_2^{NC}}{\partial \bar{q}_1} + \delta (\bar{X}_3 - b \bar{q}_3^{NC}) \frac{\partial \bar{q}_3^{NC}}{\partial \bar{q}_1} \right) \\
&\quad + \delta \nu_0 (1 - x) \left((\underline{X}_2 - b \underline{q}_2^{FB}(\bar{\nu}_1)) \frac{\partial \underline{q}_2^{FB}(\bar{\nu}_1)}{\partial \bar{q}_1} + \delta (\underline{X}_3 - b \underline{q}_3^{FB}(\bar{\nu}_1)) \frac{\partial \underline{q}_3^{FB}(\bar{\nu}_1)}{\partial \bar{q}_1} \right)
\end{aligned}$$

By replacing: $\frac{\partial \underline{q}_2^{FB}(\bar{\nu}_1)}{\partial \bar{q}_1} = \frac{\partial \bar{q}_2^{NC}}{\partial \bar{q}_1} = -\frac{\delta}{1+\delta}$ and $\frac{\partial \underline{q}_3^{FB}(\bar{\nu}_1)}{\partial \bar{q}_1} = \frac{\partial \bar{q}_3^{NC}}{\partial \bar{q}_1} = -\frac{1}{1+\delta}$, I can rewrite:

$$\begin{aligned}
\frac{\partial U_R^{NC}}{\partial \bar{q}_1} &= -\Delta \theta \nu_0 x \frac{(1 - \delta) (2\delta + 1)}{1 + \delta} + (1 - \nu_0 x) \left(\bar{X}_1 - b \bar{q}_1 - \frac{\delta^2}{1 + \delta} (\bar{X}_2 + \bar{X}_3 - b (S - \bar{q}_1)) \right) = 0 \\
\bar{q}_1^{NC} &= \bar{q}_1^{FB} - \frac{(1 - \delta) (2\delta + 1) \Delta \theta \nu_0 x}{b (\delta^2 + \delta + 1) (1 - \nu_0 x)}
\end{aligned}$$

¹³Without commitment, if the stock is not exhausted, during the first period, full separation is optimal, and an inefficient firm produces the same as with commitment: $\frac{\bar{X}_1}{b} - \frac{\Delta \theta}{b(1-\nu_0)}$, and then produces the first best: $(\frac{\bar{X}_2}{b}, \frac{\bar{X}_3}{b})$. Thus, both types exhaust the stock if: $\frac{\bar{X}_1}{b} - \frac{\Delta \theta}{b(1-\nu_0)} + \frac{\bar{X}_2}{b} + \frac{\bar{X}_3}{b} > S$.

The optimal separation level is given by:

$$\begin{aligned} \frac{\partial U_R^{NC}}{\partial x} = & \delta (1 - \nu_0) \left(\frac{\partial \bar{T}_2^{FB}}{\partial x} + \delta \frac{\partial \bar{T}_3^{FB}}{\partial x} \right) - \delta \Delta \theta \nu_0 \left(\frac{\partial \bar{q}_2^{NC}}{\partial x} + \delta \frac{\partial \bar{q}_3^{NC}}{\partial x} \right) \\ & + \nu_0 \left(\underline{T}_1^{FB} - \bar{T}_1^{FB} - \Delta \theta \bar{q}_1^{NC} + \delta \left(\underline{T}_2^{FB}(\nu_1) - \underline{T}_2^{FB}(\bar{\nu}_1) + \delta \left(\underline{T}_3^{FB}(\nu_1) - \underline{T}_3^{FB}(\bar{\nu}_1) \right) \right) \right) \end{aligned}$$

$$\frac{\partial \bar{q}_1^{NC}}{\partial x} = 0, \quad \frac{\partial \bar{q}_2^{NC}}{\partial x} = \frac{(1-\delta) \Delta \theta \nu_0}{b(\delta+1)(1-\nu_0)} \quad \text{and} \quad \frac{\partial \bar{q}_3^{NC}}{\partial x} = -\frac{(1-\delta) \Delta \theta \nu_0}{b(\delta+1)(1-\nu_0)}. \quad \text{Therefore:}$$

$$\frac{\partial U_R^{NC}}{\partial x} = \frac{(1-\delta)^2 \Delta \theta^2 \nu_0}{b(\delta+1)} \left(\frac{(2\delta+1)^2}{2(\delta^2+1+\delta)(1-\nu_0 x)^2} - \frac{\delta \nu_0 x}{1-\nu_0} \right) > 0, \quad \forall \delta \in [0, 1], x \in [0, 1], \nu_0 \in [0, 1].$$

$$x^* = 1, \quad \bar{q}_1^{NC} = \bar{q}_1^{FC} \text{ defined by (43) and } \bar{S}_2^{NC} = \bar{S}_2^{FC} = S - \bar{q}_1^{FC} > \bar{S}_2^{FB} = S - \bar{q}_1^{FB}.$$

One can easily show that cost of asymmetric information without commitment is larger than with

$$\text{commitment: } C^{NC} - C^{FC} = \frac{(1-\delta)^2 \delta \Delta \theta^2 \nu_0^2}{2b(1+\delta)(1-\nu_0)} > 0$$

D Optimal contract duration

In what follows, I consider different cases to show that Corollary 1 and 2 hold. I do not define the entire set of conditions under which these cases occur.

Corollary 1:

The inability to commit may decrease the efficient firm's contract duration as compared to the first best. Assume that under symmetric information, both firms exhaust the stock during the third period. Then, from (41), $\delta \underline{X}_3 - \underline{X}_2 + b \underline{S}_2^{FB} > 0$ and $\delta \bar{X}_3 - \bar{X}_2 + b \bar{S}_2^{FB} > 0$. Assume that without commitment, both firms also exhaust the stock during the third period, and that during the first period, it is optimal to fully separate firms and that both (IC) bind. This implies that full-separating contracts where only (IC) binds are not incentive compatible, therefore: $\underline{q}_1^{FB} < \bar{q}_1^{FC} + \delta \bar{q}_2^{FB}(\bar{S}_2^{FC}) + \delta^2 \bar{q}_3^{FB}(\bar{S}_2^{FC})$, where $\bar{S}_2^{FC} = S - \bar{q}_1^{FC}$, and \underline{q}_1^{FB} , $\bar{q}_2^{FB}(\bar{S}_2^{FC})$, $\bar{q}_3^{FB}(\bar{S}_2^{FC})$ and \bar{q}_1^{FC} are respectively given by (42), (39), (40) and (43). Under full-separating contracts where both (IC) bind, if both firms exhaust the stock during the third period, it is easy to show that the

efficient firm's extraction is:

$$\underline{q}_1^{NC} = \underline{q}_1^{FB} + \frac{(1-\delta)(1-\nu_0)}{4\delta^2(\delta^2-\delta-1)\nu_0+\delta^2+2\delta+1} (\bar{q}_1^{FC} + \delta \bar{q}_2^{FB}(\bar{S}_2^{FC}) + \delta^2 \bar{q}_3^{FB}(\bar{S}_2^{FC}) - \underline{q}_1^{FB})$$

Since $4\delta^2(\delta^2-\delta-1)\nu_0+\delta^2+2\delta+1 > 0$, and since both (IC) bind implies $\bar{q}_1^{FC} + \delta \bar{q}_2^{FB}(\bar{S}_2^{FC}) + \delta^2 \bar{q}_3^{FB}(\bar{S}_2^{FC}) - \underline{q}_1^{FB} > 0$, $\underline{q}_1^{NC} > \underline{q}_1^{FB} \Leftrightarrow \underline{S}_2^{NC} = S - \underline{q}_1^{NC} < \underline{S}_2^{FB} = S - \underline{q}_1^{FB}$. In the second period, an efficient firm produces the first best, but the available stock is lower than under symmetric information. Using (41), if $\delta \underline{X}_3 - \underline{X}_2 + b \underline{S}_2^{NC} < 0$, under asymmetric information without commitment, it is optimal for an efficient firm to exhaust the stock during the second period, while under symmetric information, this firm exhausts the stock during the third period.

Without commitment, the inefficient firm's contract duration may be longer than with commitment.

Assume that with commitment, both firms exhaust the stock during the second period. Then, from (41), $\delta \underline{X}_3 - \underline{X}_2 + b \underline{S}_2^{FB} < 0$, and from (45), $(1-\nu_0)(\delta \bar{X}_3 - \bar{X}_2 + b \bar{S}_2^{FC}) + (1-\delta)\Delta\theta\nu_0 < 0$. Assume that without commitment, it is optimal in the first period to implement full-separating contracts where both (IC) bind. In the second period, the first-best contracts are implemented, and from (41), an inefficient exhausts the stock during the second period, if $\delta \bar{X}_3 - \bar{X}_2 + b \bar{S}_2^{NC} < 0$, where $\bar{S}_2^{NC} = S - \bar{q}_1^{NC}$ and \bar{q}_1^{NC} is given by (21). Since $\bar{q}_1^{NC} < \bar{q}_1^{FC}$ where \bar{q}_1^{FC} is given by (36), $\bar{S}_2^{NC} > \bar{S}_2^{FC}$, and thus $\delta \bar{X}_3 - \bar{X}_2 + b \bar{S}_2^{NC} > 0$ is compatible with $(1-\nu_0)(\delta \bar{X}_3 - \bar{X}_2 + b \bar{S}_2^{FC}) + (1-\delta)\Delta\theta\nu_0 < 0$. In other word, $\bar{q}_3^{FB}(\bar{S}_2^{NC}) > 0$ is compatible with $\bar{q}_3^{FC}(\bar{S}_2^{FC}) < 0$, and thus, without commitment, an inefficient firm may exhaust the stock during the third period, while with commitment, it exhausts the stock during the second period.

Note that under full-separating contracts where both (IC) bind, if an efficient firm exhausts the stock during the second period, while an inefficient firm exhausts the stock during the third period, it is easy to show that the first-period extractions are:

$$\begin{aligned} \underline{q}_1^{NC} &= \underline{q}_1^{FB} + \frac{(\delta^2+\delta+1)(1-\nu_0)}{(\delta-4\delta^2(1-\delta^2+\delta))\nu_0+\delta^2+\delta+1} (\bar{q}_1^{FC} + \delta \bar{q}_2^{FB}(\bar{S}_2^{FC}) + \delta^2 \bar{q}_3^{FB}(\bar{S}_2^{FC}) - \underline{q}_1^{FB}) \\ \bar{q}_1^{NC} &= \bar{q}_1^{FC} - \frac{(1-\delta)(\delta+1)(2\delta+1)\nu_0}{(\delta-4\delta^2(1-\delta^2+\delta))\nu_0+\delta^2+\delta+1} (\bar{q}_1^{FC} + \delta \bar{q}_2^{FB}(\bar{S}_2^{FC}) + \delta^2 \bar{q}_3^{FB}(\bar{S}_2^{FC}) - \underline{q}_1^{FB}) \end{aligned}$$

Corollary 2:

The inability to commit may increase the efficient firm's contract duration as compared to the first best. Assume that under symmetric information, it is optimal for an efficient firm to exhaust the stock during the second period, and for an inefficient firm to exhaust the stock during the third period. Then, from (41), $\delta \underline{X}_3 - \underline{X}_2 + b \underline{S}_2^{FB} < 0$ and $\delta \bar{X}_3 - \bar{X}_2 + b \bar{S}_2^{FB} > 0$. If without commitment, it is optimal to propose during the first period a pooling contract, and during the second period full-separating contracts where only (*IC*) binds, then, it may be optimal for an efficient firm to exhaust the stock during the third period. If so, the first-period extraction is \bar{q}_1^{FB} given by (42), and $\bar{q}_1^{FB} < q_1^{FB}$ implies $\bar{S}_2^{FB} > \underline{S}_2^{FB}$. Thus, $\delta \underline{X}_3 - \underline{X}_2 + b \bar{S}_2^{FB} > 0$ is compatible with $\delta \underline{X}_3 - \underline{X}_2 + b \underline{S}_2^{FB} < 0$.

Note that if during the first period a pooling contract is implemented, and during the second period, full-separating contracts where only (*IC*) binds are proposed, if an efficient firm exhausts the stock during the second period, while an inefficient firm exhausts the stock during the third period, it is easy to show that the first-period extraction q_1^P is given by the following first-order condition: $\frac{(1+\delta)\bar{X}_1 - \delta^2(\bar{X}_3 + \bar{X}_2 - bS) - b(\delta^2 + \delta + 1)q_1^P}{1+\delta} + \frac{\delta\nu_0(\delta\underline{X}_3 - \underline{X}_2 + b(S - q_1^P))}{1+\delta} = 0$, which implies from $\delta \underline{X}_3 - \underline{X}_2 + b(S - q_1^P) < 0$ and (42), that $q_1^P < \bar{q}_1^{FB}$.

Without commitment, the inefficient firm's contract duration may be shorter than with commitment. Assume that under information asymmetry and full commitment, an efficient firm exhausts the stock during the second period, while an inefficient firm exhausts the stock during the third period. Then, from (41), $\delta \underline{X}_3 - \underline{X}_2 + b \underline{S}_2^{FB} < 0$, and from (45), $(1 - \nu_0)(\delta \bar{X}_3 - \bar{X}_2 + b \bar{S}_2^{FC}) + (1 - \delta)\Delta\theta\nu_0 > 0$. Assume that without commitment, during the first period, it is optimal to propose full-separating contracts where only (*IC*) binds. If the inefficient firm exhausts the stock during the third period, in the first period, it produces the same as under full commitment, that is \bar{q}_1^{FC} given by (43). However, in the second period, it produces the first best: $\bar{q}_2^{FB}(S_2^{FC})$ given by (39), and thus, more than under full commitment. Hence, the stock available at the end of the second period is lower without commitment. Since $\delta \bar{X}_3 - \bar{X}_2 + b \bar{S}_2^{FC} < 0$ is compatible with $(1 - \delta)\Delta\theta\nu_0 + (1 - \nu_0)(\delta \bar{X}_3 - \bar{X}_2 + b \bar{S}_2^{FC}) > 0$, it may be optimal for an inefficient firm to exhaust

the stock during the second period without commitment, while it exhausts the stock during the third period with commitment.

E The stock is not exhausted

No countervailing incentive:

$\frac{\partial U_R^{NC}}{\partial \bar{q}_1} = -\nu_0 x \Delta \theta + (1 - \nu_0 x) (\bar{X}_1 - b \bar{q}_1) = 0$ gives $\bar{q}_1^{NC} = \bar{q}_1^{FB} - \frac{\Delta \theta \nu_0 x}{b(1-\nu_0 x)}$. From the envelope theorem, $\frac{\partial \bar{q}_1^{NC}}{\partial x} = 0$, however, $\frac{\partial \bar{q}_2^{NC}(\bar{\nu}_1)}{\partial x} = \frac{\Delta \theta \nu_0}{b(1-\nu_0)}$ since $\bar{q}_2^{NC}(\bar{\nu}_1) = \bar{q}_2^{FB} - \frac{\Delta \theta \nu_0 (1-x)}{b(1-\nu_0)}$. The separation level is given by: $\frac{\partial U_R^{NC}}{\partial x} = \nu_0 \left(\bar{T}_1^{FB} - \bar{T}_1^{FB} - \Delta \theta \bar{q}_1^{NC} \right) + \delta \frac{\partial \bar{q}_2^{NC}(\bar{\nu}_1)}{\partial x} \left(-\nu_0 \Delta \theta + (1 - \nu_0) \frac{\partial \bar{T}_2^{FB}}{\partial \bar{q}_2^{NC}(\bar{\nu}_1)} \right)$, which is equal to: $\frac{\nu_0 \Delta \theta^2}{2b(1-\nu_0 x)^2} - \frac{\delta \Delta \theta^2 \nu_0^2 x}{b(1-\nu_0)}$. The latter is positive $\forall (\delta, \nu_0, x) \in [0, 1] \Leftrightarrow x^* = 1$.

Without commitment the welfare is lower than under full commitment, indeed:

$$C_{IR}^{NC} = \nu_0 \Delta \theta \left(\bar{q}_1^{FC} + \delta \bar{q}_2^{FB} \right) > C_{IR}^{FC},$$

$$C_{PD}^{FC} = (1 - \nu_0) \left(U(\bar{\theta}, \bar{q}_1^{FB}, 0, p_1) - U(\bar{\theta}, \bar{q}_1^{NC}, 0, p_1) \right) = \frac{\Delta \theta^2 \nu_0^2}{2b(1-\nu_0)} < C_{PD}^{FC}.$$

$$\text{Hence, } U_R^{FC} - U_R^{NC} = C_{IR}^{NC} + C_{PD}^{NC} - (C_{IR}^{FC} + C_{PD}^{FC}) = \frac{\delta \Delta \theta^2 \nu_0^2}{2b(1-\nu_0)} > 0$$

Countervailing incentive:

Using (16) in (8), the regulator's problem becomes:

$$\begin{aligned} \max_{\{q_1, \bar{q}_1, x, y\}} U_R^{NC} &= (\nu_0 x + (1 - \nu_0) y) \left(\bar{T}_1^{FB} - \Delta \theta \bar{q}_1 \right) + (\nu_0 (1 - x) + (1 - \nu_0) (1 - y)) \bar{T}_1^{FB} \\ &\quad + \delta (1 - \nu_0) \left((1 - y) \bar{T}_2^{FB}(\bar{\nu}_1) + y \bar{T}_2^{FB}(\underline{\nu}_1) \right) \\ &\quad + \delta \nu_0 \left(x \left(\bar{T}_2^{FB}(\underline{\nu}_1) - \Delta \theta \bar{q}_2(\underline{\nu}_1) \right) + (1 - x) \left(\bar{T}_2^{FB}(\bar{\nu}_1) - \Delta \theta \bar{q}_2(\bar{\nu}_1) \right) \right) \end{aligned} \quad (46)$$

subject to $(SC_1), (SC_2), (SC_3), (SC_4), (17)$

Using (17) and by deriving (46) with respect to \bar{q}_1 , I get:

$$\frac{\partial U_R^{NC}}{\partial \bar{q}_1} = \bar{X}_1 - b \bar{q}_1 - \delta b (\nu_0 x + (1 - \nu_0) y) (\bar{q}_2(\bar{\nu}_1) - \bar{q}_2(\underline{\nu}_1)) = 0$$

$$\bar{q}_1^{NC} = \bar{q}_1^{FB} - \delta (\nu_0 x + (1 - \nu_0) y) (\bar{q}_2(\bar{\nu}_1) - \bar{q}_2(\underline{\nu}_1)) \quad (47)$$

$$\underline{q}_1^{NC} = \bar{q}_1^{FB} + \delta (\nu_0 (1 - x) + (1 - \nu_0) (1 - y)) (\bar{q}_2(\bar{\nu}_1) - \bar{q}_2(\underline{\nu}_1)) \quad (48)$$

Under full separation (FS), $x = 1$ and $y = 0$, thus, $\bar{q}_2(\bar{\nu}_1) = \bar{q}_2^{FB}$ and $\bar{q}_2(\underline{\nu}_1) = 0$. From (47) and (48), $\bar{q}_1^{FS} = \bar{q}_1^{FB} - \delta \nu_0 \bar{q}_2^{FB} = \bar{q}_1^{FC} - \nu_0 (\bar{q}_1^{FC} + \delta \bar{q}_2^{FB} - \underline{q}_1^{FB})$ and $\underline{q}_1^{FS} = \bar{q}_1^{FB} + \delta (1 - \nu_0) \bar{q}_2^{FB} = \underline{q}_1^{FB} - (1 - \nu_0) (\bar{q}_1^{FC} + \delta \bar{q}_2^{FB} - \underline{q}_1^{FB})$. Since there is a countervailing incentive, $\bar{q}_1^{FC} + \delta \bar{q}_2^{FB} > \underline{q}_1^{FB}$, thus, $\underline{q}_1^{FS} > \underline{q}_1^{FB} = \underline{q}_1^{FC}$ and $\bar{q}_1^{FS} < \bar{q}_1^{FC} < \bar{q}_1^{FB}$.

Under semi-separating contracts where the inefficient firm randomizes (SS^y): $x = 1$ and $y > 0$, $\bar{q}_2(\bar{\nu}_1) = \bar{q}_2^{FB}$ and $\bar{q}_2(\underline{\nu}_1) = \bar{q}_2^{FB} - \frac{\nu_0 \Delta \theta}{b(1-\nu_0)y}$. From (47) and (48), $\bar{q}_1^{SS^y} = \bar{q}_1^{FB} - \delta (\nu_0 + (1 - \nu_0)y) (\bar{q}_2^{FB} - \bar{q}_2(\underline{\nu}_1))$ and $\underline{q}_1^{SS^y} = \bar{q}_1^{FB} + \delta (1 - \nu_0) (1 - y) (\bar{q}_2^{FB} - \bar{q}_2(\underline{\nu}_1))$. The optimal level of separation is determined by solving:

$$\begin{aligned} \max_y U_R^{NC} = & (\nu_0 + (1 - \nu_0)y) \left(\underline{T}_1^{FB} - \Delta \theta \underline{q}_1^{SS^y} \right) + (1 - \nu_0)(1 - y) \bar{T}_1^{FB} + \delta \nu_0 \left(\underline{T}_2^{FB}(\underline{\nu}_1) - \Delta \theta \bar{q}_2(\underline{\nu}_1) \right) \\ & + \delta (1 - \nu_0) \left(y \bar{T}_2^{FB}(\underline{\nu}_1) + (1 - y) \bar{T}_2^{FB}(\bar{\nu}_1) \right) \end{aligned} \quad (49)$$

From the envelope theorem, $\frac{\partial \bar{q}_1^{SS^y}}{\partial y} = 0$, and from (17), $\frac{\partial \underline{q}_1^{SS^y}}{\partial y} = -\delta \frac{\partial \bar{q}_2(\underline{\nu}_1)}{\partial y} = -\delta \left(\frac{\nu_0 \Delta \theta}{b(1-\nu_0)y^2} \right)$.

$$\begin{aligned} \frac{\partial U_R^{NC}}{\partial y} = & (1 - \nu_0) \left(\underline{T}_1^{FB} - \Delta \theta \underline{q}_1^{SS^y} - \bar{T}_1^{FB} + \delta \bar{T}_2^{FB}(\underline{\nu}_1) - \delta \bar{T}_2^{FB}(\bar{\nu}_1) \right) \\ & + (\nu_0 + (1 - \nu_0)y) \left(\frac{\partial \underline{T}_1^{FB}}{\partial \underline{q}_1^{SS^y}} - \Delta \theta \right) \frac{\partial \underline{q}_1^{SS^y}}{\partial y} + \delta \frac{\partial \bar{q}_2(\underline{\nu}_1)}{\partial y} \left(-\nu_0 \Delta \theta + (1 - \nu_0)y \frac{\partial \bar{T}_2^{FB}(\underline{\nu}_1)}{\partial \bar{q}_2(\underline{\nu}_1)} \right) \end{aligned} \quad (50)$$

After simplification, (50) can be rewritten as:

$$\begin{aligned} \frac{\delta \Delta \theta^2 \nu_0^2}{2b(1-\nu_0)y^3} (2\delta \nu_0(1-y) - (1-\delta)y) &= 0 \Leftrightarrow y^* = \frac{2\delta \nu_0}{2\delta \nu_0 + 1 - \delta} \\ \bar{q}_1^{SS^y} = \bar{q}_1^{FB} - \frac{(1+\delta)\Delta\theta\nu_0}{2b(1-\nu_0)} &= \bar{q}_1^{FC} + \frac{(1-\delta)\Delta\theta\nu_0}{2b(1-\nu_0)} \Leftrightarrow \bar{q}_1^{FC} < \bar{q}_1^{SS^y} < \bar{q}_1^{FB} \\ \underline{q}_1^{SS^y} = \underline{q}_1^{FB} - \frac{(1+\delta)\Delta\theta}{2b} &\Leftrightarrow \underline{q}_1^{SS^y} < \underline{q}_1^{FB} = \underline{q}_1^{FC} \\ \bar{q}_2^{NC}(\underline{\nu}_1(1, y^*)) = \bar{q}_2^{FB} - \frac{\Delta\theta(2\delta\nu_0 + 1 - \delta)}{2b\delta(1-\nu_0)} &= \bar{q}_2^{FC} - \frac{\Delta\theta(1-\delta)}{2b\delta(1-\nu_0)} < \bar{q}_2^{FC} < \bar{q}_2^{FB} \end{aligned}$$

Since $\frac{\partial U_R^{NC}}{\partial y} \Big|_{y=1} = -\frac{\delta \Delta \theta^2 \nu_0^2}{2b(1-\nu_0)} (1-\delta) < 0$, $\forall \delta < 1$, semi-separating contracts $(x, y) = (1, y^*)$ strictly dominate a pooling contract $(x = y = 1)$. Semi-separating contracts where an efficient firm randomizes are never optimal.

F Uncorrelated types

At each period, the firm can be efficient with the probability ν , or inefficient with the complementary probability. I consider a three-period model. Under symmetric information, the regulator and the firm discover the firm's type at the beginning of each period. Under asymmetric information, the regulator does not know the firm's type, while the firm learns its type at the beginning of each period. Since the types are not correlated, there is no ratchet effect and the allocation is the same with and without commitment.

Under symmetric information: if the stock is not exhausted, the extraction is: $\frac{X_t}{b}$. If the stock is exhausted, the extraction is: $q_3 = S - q_1 - q_2$ and $q_2 = \frac{X_2 + b\delta S_2 - \delta(\nu \underline{X}_3 + \nu \bar{X}_3)}{b(1+\delta)}$ where $S_2 = S - q_1$. Knowing that the second-best contracts will be implemented in the second and third periods, the first-period extraction is: $q_1 = \frac{(1+\delta)X_1 - \delta^2((1-\nu)(\bar{X}_2 + \bar{X}_3) + \nu(\underline{X}_2 + \underline{X}_3) - bS)}{b(\delta^2 + \delta + 1)}$.

Under asymmetric information: if the stock is not exhausted, at each period, an efficient firm extracts the first best, while an inefficient firm extracts $\frac{\bar{X}_t}{b} - \frac{\Delta\theta\nu}{b(1-\nu)}$. If the stock is exhausted during the third period, for a given stock $S_2 = S - q_1$ where $q_1 = \{\underline{q}_1, \bar{q}_1\}$, during the second period, the extractions are: $\underline{q}_2^{FB} + \frac{\delta\Delta\theta\nu}{b(1+\delta)}$ and $\bar{q}_2^{FB} - \frac{\Delta\theta\nu(1-\delta(1-\nu))}{b(1+\delta)(1-\nu)}$. Knowing that the second-best contracts will be implemented in the second and third periods, the first-period extraction is: $\underline{q}_1 = \underline{q}_1^{FB} + \frac{2\delta^2\nu\Delta\theta}{b(\delta^2 + \delta + 1)}$ and $\bar{q}_1 = \bar{q}_1^{FB} - \frac{\nu\Delta\theta(1+\delta-2\delta^2(1-\nu))}{b(\delta^2 + \delta + 1)(1-\nu)}$.

G Recap Table

	Only (\underline{IC}) binds	(\underline{IC}) and (\overline{IC}) bind	
	Full separation	Full separation	Full pooling
low stock	$\delta < \delta_1$	$\delta_1 < \delta < \delta_2$	$\delta_2 < \delta < 1$
	$\underline{q}_1^{NC} = \underline{q}_1^{FB} = \underline{q}_1^{FC}$ $\bar{q}_1^{FC} = \bar{q}_1^{NC} < \bar{q}_1^{FB}$	$\underline{q}_1^{NC} > \underline{q}_1^{FB} = \underline{q}_1^{FC}$ $\bar{q}_1^{NC} < \bar{q}_1^{FC} < \bar{q}_1^{FB}$	$\underline{q}_1^{NC} = \bar{q}_1^{FB} < \underline{q}_1^{FB} = \underline{q}_1^{FC}$ $\bar{q}_1^{NC} = \bar{q}_1^{FB} > \bar{q}_1^{FC}$
	Full separation	Full separation	Semi separation
large stock	$\underline{q}_1^{NC} = \underline{q}_1^{FB} = \underline{q}_1^{FC}$	$\underline{q}_1^{NC} > \underline{q}_1^{FC} = \underline{q}_1^{FB}$	$\bar{q}_1^{FB} < \underline{q}_1^{NC} < \underline{q}_1^{FB} = \underline{q}_1^{FC}$
	$\bar{q}_1^{NC} = \bar{q}_1^{FC} < \bar{q}_1^{FB}$	$\bar{q}_1^{NC} < \bar{q}_1^{FC} < \bar{q}_1^{FB}$	$\bar{q}_1^{FC} < \bar{q}_1^{NC} < \bar{q}_1^{FB}$
	$\underline{q}_2^{NC} = \underline{q}_2^{FB} = \underline{q}_2^{FC}$	$\underline{q}_2^{NC} = \underline{q}_2^{FB} = \underline{q}_2^{FC}$	$\underline{q}_2^{NC} = \underline{q}_2^{FB} = \underline{q}_2^{FC}$
	$\bar{q}_2^{NC} = \bar{q}_2^{FB} > \bar{q}_2^{FC}$	$\bar{q}_2^{NC} = \bar{q}_2^{FB} > \bar{q}_2^{FC}$	$\bar{q}_2^{NC}(\bar{\nu}_1) = \bar{q}_2^{FB} > \bar{q}_2^{FC}$ $\bar{q}_2^{NC}(\underline{\nu}_1) < \bar{q}_2^{FC} < \bar{q}_2^{FB}$

Table 1: Extraction path

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