cirano
Allier savoir et décision

2015s-17

The management of natural resources under asymmetry of information

Gérard Gaudet, Pierre Lasserre

Série Scientifique/Scientific Series

2015s-17

The management of natural resources under asymmetry of information

Gérard Gaudet, Pierre Lasserre

Série Scientifique
Scientific Series

Montréal
Avril 2015

CIRANO
Allier savoir et décision

Centre interuniversitaire de recherche en analyse des organisations

CIRANO

Le CIRANO est un organisme sans but lucratif constitué en vertu de la Loi des compagnies du Québec. Le financement de son infrastructure et de ses activités de recherche provient des cotisations de ses organisations-membres, d'une subvention d'infrastructure du Ministère de l'Économie, de l'Innovation et des Exportations, de même que des subventions et mandats obtenus par ses équipes de recherche.

CIRANO is a private non-profit organization incorporated under the Québec Companies Act. Its infrastructure and research activities are funded through fees paid by member organizations, an infrastructure grant from the Ministère de l' l'Économie, de l'Innovation et des Exportations, and grants and research mandates obtained by its research teams.

Les partenaires du CIRANO

Partenaire majeur
Ministère de l'Économie, de l'Innovation et des Exportations

Partenaires corporatifs
Autorité des marchés financiers
Banque de développement du Canada
Banque du Canada
Banque Laurentienne du Canada
Banque Nationale du Canada
Bell Canada
BMO Groupe financier
Caisse de dépôt et placement du Québec
Fédération des caisses Desjardins du Québec
Financière Sun Life, Québec
Gaz Métro
Hydro-Québec
Industrie Canada
Intact
Investissements PSP
Ministère des Finances et de l'Économie
Power Corporation du Canada
Rio Tinto Alcan
Ville de Montréal

Partenaires universitaires
École Polytechnique de Montréal
École de technologie supérieure (ÉTS)
HEC Montréal
Institut national de la recherche scientifique (INRS)
McGill University
Université Concordia
Université de Montréal
Université de Sherbrooke
Université du Québec
Université du Québec à Montréal
Université Laval

Le CIRANO collabore avec de nombreux centres et chaires de recherche universitaires dont on peut consulter la liste sur son site web.

ISSN 2292-0838 (en ligne)

Partenaire financier
Économie, Innovation et Exportations Québec

The management of natural resources under asymmetry of information*

Gérard Gaudet†, *Pierre Lasserre*‡

Résumé/abstract

We provide an introductory review to the application of the theory of incentives under asymmetry of information to the exploitation and management of natural resources. We concentrate mostly on principalagent problems with adverse selection as posed by the regulation of nonrenewable resources, stressing the fact that the inherently dynamic nature of natural resource exploitation creates situations and results not found in other contexts. We also point out private information issues that may arise involving renewable as opposed to nonrenewable resources, strategic interactions with signalling between decision makers in resource exploitation games, and the design of environmental policy where principal-agent problems subject to moral hazard may occur.

Mots clés : Natural resources, asymmetric information, agency.

---

* This paper will be published in Annual Reviews : http://www.annualreviews.org/page/authors/author-instructions/econ , When citing this paper, please use the following: Gaudet G, Lasserre P. 2015. The management of natural resources under asymmetry of information. Annu. Rev. Econ. 3: Doi: 10.1146/annurev-resource-100814-124959.

† Département de sciences économiques and CIREQ, Université de Montréal, C. P. 6128, succursale Centre-ville, Montréal (Québec) H3C 3J7 CANADA (gerard.gaudet@umontreal.ca)

‡ Département des sciences économiques, Université du Québec à Montréal, CIREQ and CIRANO, C.P. 8888, succursale A, Montréal, Québec H3C 3P8, CANADA (lasserre.pierre@uqam.ca)

1. Introduction

A situation of asymmetric information occurs when one of the parties involved in a strategic relationship has private information about some important element relevant to the relationship. There now exists an important literature that deals with such problems as they arise in economic relationships.[1] Our purpose is to provide an overview of how the known methods of analysis proposed in that literature can be adapted for application to the particular problem of the regulation of natural resource exploitation.

A large part of the existing economics literature on the subject deals with static situations: situations where the strategic interaction takes place in a single period. When dynamic situations are considered, the source of the dynamics is usually the evolution of the information itself. In other words, if, in a multi-period situation the variable that is subject to private information is correlated over time then the information "state" may change over time through learning. This of course raises a number of complications for the analysis of the problem as compared to the static situation.[2] Natural resource exploitation has the particularity that it is an inherently dynamic problem, which can only be properly analyzed in a multi-period setting (or in continuous time), irrespective of whether the information state evolves over time. This is because the resource stock itself is a state variable that necessarily changes over time as exploitation of the resource takes place. There are then potentially two sources of dynamics: a source that is specific to the information problem itself, which arises when the true value of the variable subject to asymmetry of information changes over time; a source that is specific to the resource exploitation problem, which arises because of the intertemporal link inherent to the problem, resulting in future decisions being physically constrained by current decisions.

The existing literature on the theory of incentives has adopted a useful classification and nomenclature for the different types of situations that can arise. Thus, when the uninformed party moves first we have a *principal-agent* problem, the principal being the uninformed party. The private information held by the agent is then about some *endogenous* variable, such as the agent's discretionary actions (the generic term "*effort*" is often used to describe those actions), or it can be about some *exogenous* characteristic of the agent, such as some technological constraints faced by the agent (production costs for instance). In the former case we have a principal-agent problem with *moral hazard*; in the latter case, we have a principal-agent problem with *adverse selection*. When the private information is about some exogenous variable but the informed party moves first, we have a *signalling* problem instead of a principal-agent problem. Except for a brief discussion of other possibilities in Section 5, we will restrict attention in what follows to the principal-agent problem with adverse selection.

The problem we will consider is that of the owner of a nonrenewable resource stock (the "principal") who delegates the extraction of the resource to a specialized firm (the "agent") through a contractual arrangement that specifies a payment scheme from the firm to the owner, designed to maximize the owner's objective function. This objective function can be some measure of expected social welfare if the resource is owned by a government, or possibly just the expected total revenue, especially if there is private ownership of the resource stock. In choosing the payment scheme the owner must take into account the

[1] For thorough expositions of that literature see Laffont & Tirole (1993), Salanié (1997), and Laffont & Martimort (2002).

[2] See for instance Baron & Besanko (1984), Baron (1989) or Laffont & Tirole (1988, 1993).

information constraints coming from the fact that the firm has private information about the true value of some exogenous cost parameter (following the tradition of the principal-agent literature, we will occasionally call the true value of this parameter the firm's "type"). That there is then adverse selection means that unless the payment scheme is designed to prevent it, the firm has an incentive to cheat on the value of its true cost parameter in order to minimize the payment required by the owner. The payment scheme chosen by the owner becomes a mechanism designed to create an incentive for the firm to reveal its true cost. Because of the information advantage it holds, the firm will generally be in a position to extract an *information rent*, contrary to what is the case in a world of perfect information, or, if imperfect, of symmetric information. In a world of symmetric information the optimal payment scheme must bring the firm to choose its extraction path so as to have the expected marginal benefit growing at the rate of discount, a path which corresponds to the basic Hotelling rule (Hotelling 1931). The resource rent is then maximized and captured entirely by the owner. In a world of asymmetric information, the optimal incentive mechanism will generally necessitate that the extraction path satisfies a modified Hotelling rule, modified to take into account the information rent that must be left in the hands of the firm, according to its type, so as incite it to reveal its true type.

In the next section we present the simple model that will be used in Sections 3 and 4 to analyze the optimal regulation of nonrenewable resource exploitation under asymmetry of information. In that section, we also discuss the benchmark case of symmetric information, to which we can later compare the results obtained under asymmetric information. Section 3 is devoted to the optimal regulation problem with asymmetric information, distinguishing the subcases that can arise depending on whether the parameter subject to private information is temporally correlated or not, and whether the principal can commit for the full duration of the relationship or not. In Section 4 we discuss the effect of information asymmetry on the optimal terminal period. A few other issues, which we think worthy of future research, are raised in Section 5, followed by a brief conclusion in Section 6.

2. A basic model with nonrenewable resources

We begin by formulating a basic model of a situation where the owner of a nonrenewable resource stock enters into a contract with a specialized firm to which it delegates the extraction of the resource. The contract will specify a payment scheme from the firm to the owner, meant to capture the rent generated by the extraction and sale of the resource flow. For ease of exposition, we will for the most part think of the owner as a government, in which case the payment scheme can be thought of as a form of taxation; but the owner could well be a private owner and the payment scheme a form of royalty.

To keep things simple, we will assume that the country in which the resource stock is being exploited is a price taker in the world market. In such a case, the production flow from that stock does not give rise to domestic consumer surplus, so that only the revenue collected by the government and the producer surplus (the firm's profit) need enter social welfare.

Let $R_t(q_t) \geq 0$ represent the payment schedule from the firm to the owner, where q_t is the quantity extracted in period t. Then, if p_t is the price in period t and $C(q_t, \theta_t)$ the total cost of extracting q_t, the extracting firm's profit in period t net of the payment to the owner of the stock will be $\Pi(q_t, \theta_t) = p_t q_t - C(q_t, \theta_t) - R_t(q_t)$.

The price p_t will be assumed known with certainty by all. As for the total cost $C(q_t, \theta_t)$, it is assumed positively related to the parameter θ_t, which is meant to capture the firm's efficiency in exploiting the resource pool in question. This parameter is not known with certainty beforehand, but it is common knowledge that its cumulative distribution is $F(\theta_t)$, defined on the interval $[\theta^L, \theta^H]$, with density function $f(\theta_t) > 0$, assumed differentiable on $[\theta^L, \theta^H]$. The supports of the distribution, θ^L and θ^H, denote respectively the lowest and highest possible cost types in the distribution.

If $W_t(q_t, \theta_t)$ is the social welfare generated in period t by the extraction program, then a social welfare maximizing government would wish to choose the payment schedule $R_t(q_t)$, for all t so as to maximize

$$\sum_{t=1}^{\infty} \delta^{t-1} EW_t(q_t, \theta_t), \tag{1}$$

where

$$EW_t(q_t, \theta_t) = \int_{\theta^L}^{\theta^H} W_t(q_t, \theta_t) f(\theta_t) d\theta_t \tag{2}$$

and $0 < \delta = 1/(1+r) < 1$ is the discount factor, r being the discount rate. Since we can ignore consumer surplus, the social welfare in period t can be written as the sum of government revenue and a portion α of the profits left to the firm:

$$W_t(q_t, \theta_t) = R_t(q_t) + \alpha \Pi(q_t, \theta_t). \tag{3}$$

It is assumed that $0 \leq \alpha < 1$, which means that a dollar in government revenue is valued more highly than a dollar left in the hands of the firm. Otherwise, if $\alpha \geq 1$, the maximization of (1) is attained when the discounted flow of profits is maximized and the solution is then trivial: the government should simply set $R_t(q_t) = 0$ and leave the decision making to the firm, knowing that it will choose the extraction program so as to maximize the discounted flow of expected profits.

Notice that the case where the owner only wishes to maximize the discounted flow of revenues collected can be accounted for as a special case by simply setting $\alpha = 0$. This seems like an appropriate representation of the objective of a private owner, who has no a priori reason to care about the profit left to the firm. Of course, in some circumstances, it could also be the objective of a government owner.

To be feasible, the choice of $R_t(q_t)$ by the owner and the resulting q_t by the firm must of course satisfy the nonrenewability constraint $\sum_{t=1}^{\infty} q_t \leq X_1$, where X_1 is the stock available at the beginning of period 1. In order to be implementable, the payment scheme must also leave the firm with enough surplus to cover its opportunity cost, for otherwise it would rationally choose to drop out, which it can do at the beginning of any period. This is the so-called "participation constraint". We will, without loss of generality, assume the firm's opportunity cost to be zero.

For expositional purposes, it will help to assume a quadratic cost function, as in Gaudet, Lasserre & Long (1995). Total cost will henceforth take the form

$$C(q_t, \theta_t) = \theta_t q_t + \frac{b}{2} q_t^2 \tag{4}$$

with marginal cost

$$MC((q_t, \theta_t) = \theta_t + b q_t, \tag{5}$$

where $b \geq 0$ is assumed known by all with certainty. For the same reason, we will also assume for now that the optimal terminal period does not exceed $t = 2$.[3] This could be because demand for the resource in question falls to zero after period 2, for whatever reasons — the known appearance of a cheap perfectly substitutable and inexhaustible backstop for instance. If X_t denotes the remaining stock at the beginning of period t, then $X_2 = X_1 - q_1$ and we must have $q_1 \leq X_1$, and $q_2 \leq X_2$.

As a useful benchmark, consider first a situation of symmetric information, where the government fully shares the firm's information on θ_t. We will limit attention to the case where it is then optimal to require that all firm types exhaust the initial stock by the end of the second period. In order to guarantee this it is sufficient to assume that the marginal profit of extracting the whole of the initial stock X_1 in period 2 is non negative for the highest cost type. The first-order condition for an interior solution in period 2 being

$$p_2 - \theta_2 - bq_2 = 0, \tag{6}$$

this means that we will assume throughout that

$$p_2 \geq \theta^H + bX_1. \tag{7}$$

As shown in Gaudet, Lasserre & Long (1995), for an interior solution in period 1, so that production is positive in both periods, the extraction path must then satisfy

$$p_1 - \theta_1 - bq_1 = \delta(p_2 - E\theta_2 - b[X_1 - q_1]). \tag{8}$$

This is the usual Hotelling rule (Hotelling 1931), which yields the efficient extraction path, given by

$$q_1^*(\theta_1, X_1) = \frac{p_1 - \theta_1 - \delta[p_2 - E\theta_2 - bX_1]}{(1+\delta)b} \qquad \text{and} \qquad q_2^*(\theta_1, X_1) = X_1 - q_1^*(\theta_1, X_1). \tag{9}$$

It says that marginal profit must be growing at the rate of discount. One implication is that, keeping everything else the same (i.e. setting $p_2 = p_1$ and $E\theta_2 = \theta_1$), if the discount rate is positive (i.e. $\delta < 1$) the extraction path will be tilted towards the present: a smaller quantity will be extracted in period 2 than in period 1 (i.e. $q_2^* < q_1^*$).

In the symmetric information scenario, since the government is able to verify, along with the firm, the true value of θ_t at the beginning of each period, it will be able to propose a payment schedule based on the true extraction cost. The following payment schedule will ensure that the firm chooses the above efficient extraction path:

$$R_t(q_t) = \begin{cases} \left[p_t - \theta_t - \dfrac{b}{2}q_t\right] q_t & \text{if} \quad q_t = q_t^*(\theta_t, X_t) \\ \left[p_t - \theta_t - \dfrac{b}{2}q_t\right] q_t + k, \quad k > 0 & \text{if} \quad q_t \neq q_t^*(\theta_t, X_t) \end{cases} \tag{10}$$

for $t = 1, 2$. The present value of the resource rent will be maximized and entirely captured by the government.

[3]We will discuss briefly the robustness of this assumption in the presence of asymmetry of information at the end of Section 3.1 and the endogenous determination of the optimal terminal period in Section 4.

With this basic model and benchmark case in mind, we may now turn to the situation of asymmetric information, which occurs when the true value of θ_t is known to the firm, but not to the government. The government's information is then limited to the distribution of θ_t. As a consequence, although it can observe the quantity extracted, it cannot propose a payment schedule, $R_t(q_t)$, based on the true cost of extraction, which it is unable to verify.

But before we can tackle the analysis of the optimal payment schedule under asymmetric information, we need to specify our assumptions concerning the ability of the government to commit over time and concerning the information dynamics. The issues are whether the government is able to commit to the announced payment scheme for more than one period and whether the true value of the cost parameter is correlated over time. We can distinguish four possible sets of assumptions relating to those two issues:

Possibility 1: No intertemporal commitment on the part of the government and no intertemporal correlation of the cost parameter;

Possibility 2: Full intertemporal commitment on the part of the government and no intertemporal correlation of the cost parameter;

Possibility 3: No intertemporal commitment on the part of the government and intertemporal correlation of the cost parameter;

Possibility 4: Full intertemporal commitment on the part of the government and intertemporal correlation of the cost parameter.

The next section is devoted to a discussion of those four possibilities.

3. Asymmetric information

3.1. No intertemporal commitment and temporally uncorrelated costs

We begin the analysis of situations where there is asymmetry of information by assuming that intertemporal commitment on the part of the government is not possible and that the cost parameter θ_t is not correlated over time.[4] The first of those assumptions means that the government can commit only to the current period's payment rule, and not to future payment rules. This is not an unreasonable assumption, to the extent that governments are often relatively short-lived and have a limited ability to bind future governments.

The second assumption is more restrictive: it amounts to assuming that at the beginning of each period the firm discovers the new value of $\theta_t \in [\theta^L, \theta^H]$, drawn from the distribution $F(\theta_t)$, which it will face for that period independently of past values. Hence the government is unable to learn anything about the firm's cost in future periods from information gained about its current cost by observing its current output.

Given those assumptions, we can make use of the *revelation principle* in solving the problem,[5] which is modelled as a *direct revelation game*. This means that the government proposes to the firm an incentive mechanism expressed "directly" in terms of the value of the cost parameter reported by the firm — call it $\tilde{\theta}_t$. Those so-called *direct incentive mechanisms* take the form of a pair $(R_t(\tilde{\theta}_t), q(\tilde{\theta}_t))$ that is optimal from the government's

---

[4]This is the scenario analyzed in Gaudet, Lasserre & Long (1995).

[5]Amongst the first to make use of the revelation principle to analyze incentive problems are Dasgupta, Hammond & Maskin (1979) and Myerson (1979). See also Laffont & Tirole (1993) and Laffont & Martimort (2002) for in depth treatments of incentive problems under asymmetric information in general and the use of the revelation principle in particular.

point of view given the $\tilde{\theta}_t$ reported by the firm. Given the proposed mechanism the firm then chooses to report the value of $\tilde{\theta}_t$ that is optimal from its point of view, conditional on its private knowledge of the true value θ_t of the cost parameter. According to the revelation principle, we can restrict attention to the class of *incentive compatible direct mechanisms*. Those are mechanisms in response to which the firm will choose to reveal its true cost parameter.[6] In other words, they are incentive schemes constructed in such a way that the firm will maximize its profit in period t by reporting $\tilde{\theta}_t = \theta_t$. Knowing $q_t(\theta_t)$ and $R_t(\theta_t)$ we can then obtain the desired payment scheme $R_t(q_t)$ as a function of q_t by inverting $q_t(\theta_t)$ to get $\theta_t = \theta_t(q_t)$.

It is useful at this point to define

$$h(\theta_t) = \frac{F(\theta_t)}{f(\theta_t)}, \qquad t = 1, 2,$$

and assume, as is common in the incentive literature, that

$$\frac{dh(\theta_t)}{d\theta_t} \geq 0, \quad t = 1, 2. \tag{11}$$

This is sometimes called the "monotone hazard rate" assumption. It will ensure incentive compatibility of the proposed payment scheme, by guaranteeing that higher-cost firms are not asked to produce more than lower-cost ones.[7]

In the symmetric information case, as in the full information case, the marginal cost to the government is the marginal cost of extraction, that is $\theta_t + bq_t$ (see (5)). Under asymmetric information, the marginal cost has to be modified by the government to take into account the information constraint it now faces. As shown in Gaudet, Lasserre & Long (1995), it becomes $\theta_t + bq_t + (1-\alpha)h(\theta_t)$ under asymmetric information. The term $(1-\alpha)h(\theta_t)$ represents the marginal *information rent* that must be left in the hands of the firm of type θ_t in period t in order to leave it with the incentive not to exaggerate its extraction cost. This rent foregone represents an opportunity cost to the government. The higher α — hence the greater the weight given to the profits left in the hands of the firm —, the lower is the distortion due to the information rent, because the foregone rent then represents a smaller loss in the government's objective function.

Now recall that, from assumption (7), $p_2 \geq \theta^H + bX_1$, which guarantees that the stock will be fully depleted in two periods for all firm types in the reference scenario of symmetric information. The right-hand side represents the marginal cost of extracting in period 2 a quantity equal to the whole initial stock under the least favorable cost scenario (i.e. $\theta_2 = \theta^H$). But the first-order condition for an interior solution in period 2 is now

$$p_2 \geq \theta_2 + bq_t + (1-\alpha)h(\theta_2), \tag{12}$$

and the equivalent to (7) under asymmetry of information is therefore

$$p_2 \geq \theta^H + bq_t + (1-\alpha)h(\theta^H). \tag{13}$$

---

[6] See Section A of the Appendix in Gaudet, Lasserre & Long (1995) for a characterization of this class of mechanisms in the present context.

[7] For a discussion of how this assumption is used to guarantee incentive compatibility see Baron (1989, pages 1371–1372). Actually, the hazard rate itself is $f(\theta_t)/(1-F(\theta_t)$, which is monotone increasing when (11) is satisfied.

Assumption (7) does not guarantee that (13) holds. Indeed, we cannot rule out $p_2 < \theta^H + bq_t + (1-\alpha)h(\theta^H)$ even though $p_2 \geq \theta^H + bX_1$. When this happens, the possibility exists that for some firm types the initial stock will not be exhausted in two periods, since the adjusted marginal profit is negative for $\theta_2 = \theta^H$ when $q_2 = X_1$.

Consider first the case where $p_2 \geq \theta^H + bq_t + (1-\alpha)h(\theta^H)$ is satisfied. It will then be optimal to have all firm types exhaust the resource stock under asymmetry of information as under symmetry of information. If we restrict attention to interior solutions in period 1, the optimal extraction path will then have to satisfy the following modified Hotelling rule:[8]

$$p_1 - \theta_1 - bq_1 - (1-\alpha)h(\theta_1) = \delta(p_2 - E\theta_2 - b[X_1 - q_1]). \tag{14}$$

It says that the marginal profit properly adjusted to take into account the cost of the informational constraint must grow at the rate of return. The resulting optimal extraction path is given by

$$q_1^a(\theta_1, X_1) = \frac{p_1 - \theta_1 - (1-\alpha)h(\theta_1) - \delta[p_2 - E\theta_2 - bX_1]}{b(1+\delta)}, \quad q_2^a(\theta_1, X_1) = X_1 - q_1^a(\theta_1, X_1). \tag{15}$$

As in the symmetric information scenario, an implication is that with a positive discount rate (i.e. $\delta < 1$) the extraction rate is decreasing (i.e. $q_2^a < q_1^a$) if the price is constant and the cost distribution is unchanged over time (i.e. $p_2 = p_1$ and $E\theta_2 = \theta_1$).

Notice that $q_1^a(\theta_1, X_1) = q_1^*(\theta_1, X_1) - (1-\alpha)h(\theta_1)/b(1+\delta)$. Therefore, since θ^L is the lower bound of the distribution of θ_t for all t, we have by definition $F(\theta^L) = 0$ and hence $h(\theta^L) = 0$. This means that the Hotelling rule and the resulting extraction path are left unchanged for the lowest-cost firm. But $F(\theta_1) > 0$ and hence $h(\theta_1) > 0$ for $\theta^L < \theta_1 \leq \theta^H$. Therefore the optimal payment scheme requires all but the lowest-cost firm to produce less in period 1 than under symmetric information and therefore more in period 2: for all but the lowest-cost firm the optimal path is tilted less in favor of the present than under symmetric information. This distortion with respect to the first-best solution that prevails under symmetric information is necessary in order to provide an incentive for the firm not to exaggerate its cost, in an attempt to reduce the payment it is asked to make to the government.

The results just described depend crucially on the fact that when $p_2 \geq \theta^H + bq_t + (1-\alpha)h(\theta^H)$ it is optimal to have the firm fully deplete the initial resource stock by the end of the final period for all θ_2, under both symmetric and asymmetric information. But if $p_2 < \theta^H + bq_t + (1-\alpha)h(\theta^H)$ we must envisage the possibility that under asymmetry of information some firm types be required not to exhaust the initial stock. Then, since the resource constraint is not binding, a change in the quantity extracted in period 1 does not have to be compensated by a change in the opposite direction in period 2 for those firm types, contrary to what is the case under the reference scenario of symmetric information. This means that the opportunity cost of extracting the resource today rather than leaving

[8] Corner solutions of the form $q_1 = 0$ or $q_1 = X_1$ can of course not be ruled out at least for some firm types. For expository purposes we will neglect them here. The possibilities of corner solutions in period 1 are analyzed in detail in Gaudet, Lasserre & Long (1995). It is shown there that whenever the optimal payment scheme under asymmetry of information requires some firm types to extract nothing in period 1, it requires more firm types to do so than it would under symmetric information. Inversely, whenever the optimal scheme requires some firm types to fully deplete the resource in period 1, it requires fewer firm types to do so than under symmetric information.

it in the ground for future extraction is lower than it would otherwise be, and lower than under symmetric information. As a result, the optimal payment scheme will tend to require less reduction in the quantity extracted in period 1 than it would if all firm types were required to exhaust their remaining stock in period 2.

As shown in Gaudet, Lasserre & Long (1995), when the optimal payment scheme requires of some firm types that they not exhaust the resource stock, it may even require any given firm type, even the lowest-cost type, to extract more in period 1 than it would under symmetric information. In fact, assuming the solution for first-period extraction to be interior under both symmetric and asymmetric information, the optimal payment scheme will then *always* require even the lowest-cost firm to extract more in the first period than it would under symmetric information. Thus, contrary to what was the case when all firm types were required to exhaust the resource stock, and contrary to the standard result concerning incentive schemes in a static relationship between the principal and the agent or a multi-period relationship without intertemporal constraints, the optimal payment scheme always induces a distortion to the lowest-cost firm.

To see the intuition behind this result it can help to rewrite the modified Hotelling rule (14), derived for the case where all firm types exhaust the resource, as

$$p_1 - \theta_1 - bq_1 = \delta(p_2 - E\theta_2 - b[X_1 - q_1]) + (1 - \alpha)h(\theta_1).$$

This highlights the fact that under asymmetric information the equilibrium net marginal benefit of first-period extraction is the sum of two terms: the first term is the discounted net expected benefit foregone by not having the marginal unit of the resource available for exploitation in the second period given that $q_2 = X_1 - q_1$, while the second term represents the necessary adjustment for the information constraint. For the lowest-cost firm the second term is zero ($h(\theta^L) = 0$), while the first term is the same as it would be under symmetric information, so that no distortion from the first-best path is required of the lowest-cost firm. However, when some firm types are required not to exhaust the resource (i.e. $q_2 < X_1 - q_1$), the net expected benefit of having the marginal unit of resource available for second-period extraction is lower than it would otherwise be. Therefore, although the second term is still zero for the lowest-cost firm (i.e. $h(\theta^L) = 0$), its opportunity cost of first-period exploitation is smaller and it becomes optimal to require even the lowest-cost firm to extract more in the first period than it would under symmetric information.

It turns out that when we relax the assumption that period 2 is the optimal terminal period, as is done in Gaudet, Lasserre & Long (1995), the necessity of distorting the extraction path of even the lowest-cost firm becomes the rule rather than the exception. Indeed, even when the optimal payment scheme requires all firm types to exhaust the remaining stock in the last period, it will always induce a distortion in the next to last period, and a fortiori in preceding periods when the optimal terminal period exceeds period 2.[9] Since distortions will then always be required in all periods between the current and the last, the opportunity cost of extracting the resource in the current period rather than leaving it for future extraction will be different under asymmetric information than under symmetric information. Hence the extraction path of the lowest-cost firm will always be affected by the optimal incentive scheme. This result, which is contrary to what is found in the

[9]See Section 5 of Gaudet, Lasserre & Long (1995) and its accompanying Appendix (Section B) for the generalization of the method of solution to an arbitrary number of periods and a detailed discussion and proof of this statement.

usual purely static framework, is due solely to the intertemporal constraint inherent to the exploitation of the resource.

3.2. Full intertemporal commitment and temporally uncorrelated costs

The assumption made so far is that the government cannot commit beyond the current period. Although such an assumption is not unreasonable in many circumstances, it seems legitimate to ask how the optimal program would differ if the resource owner could commit at the outset to a whole sequence of payment schemes for the duration of the relationship. In this section, we explore this question while maintaining the assumption of temporally uncorrelated costs.[10] One thing is certain: the owner, whether private or government, cannot do worst when it can fully commit than when it is unable to commit for more than one period. The reason is that if it can fully commit, then it can always choose to commit to the no-commitment equilibrium outcome.

When intertemporal commitment is not possible, the equilibrium payment scheme will reflect the fact that the government will respond optimally to the $\tilde{\theta}_t$ reported by the firm given the information it has at the beginning of period t. When deciding to report $\tilde{\theta}_1$ at the beginning of period 1, the firm must therefore anticipate the government's response at the beginning of period 2 to its report $\tilde{\theta}_2$. However, the firm knows, as does the government, that it will hold at the beginning of period 2 private information about its true cost, information that it may use to its advantage. This means that the government faces an adverse selection problem in both period 1 and period 2 when it can commit only to the current period's payment scheme.

When full intertemporal commitment is possible, the government is able to commit *at the beginning of the relationship* to a sequence $\{R_t(\tilde{\theta}_t), q_t(\tilde{\theta}_t) \,|\, t = 1, 2\}$ of payment schemes in response to the firm's report of $\tilde{\theta}_1$ in period 1 and $\tilde{\theta}_2$ in period 2.[11] In other words, although the firm is uncertain at the outset as to what will be its true cost in period 2, it knows with certainty what will be the government's response to its report $\tilde{\theta}_2$. Therefore it looses the possibility, when choosing its report $\tilde{\theta}_1$ at the beginning of period 1, of exploiting the private information it will hold at the beginning of period 2. This is because at the beginning of the relationship the only information it has about the true value of θ_2 is its distribution, information that is shared by the government.

In other words, since commitment with respect to the second period now occurs at the beginning of the first period, there is in fact no asymmetry of information with respect to the second period at the moment of commitment. The first-order condition for an interior solution in period 2 is therefore given by (6), the same as in the reference scenario of symmetric information. The prevailing assumption (7) will therefore guarantee that the initial stock will always be fully depleted in period 2 when the government is able to fully commit. But there remains asymmetry of information in period 1, which has repercussions for the quantity extracted in both periods since, from the resource exhaustibility constraint,

---

[10]The design of multi-period incentive mechanisms with full commitment has been analyzed, for instance, in Baron & Besanko (1984) and Baron (1989). Our problem differs in that we assume in this section, as in the previous one, temporal independence of the variable of adverse selection, but add the complication of the nonrenewability constraint.

[11]The revelation principle again allows us to restrict attention to direct incentive mechanisms in response the which the firm will choose to report its true cost, that is $\tilde{\theta}_t = \theta_t$ for $t = 1, 2$, as it did in the previous section, where the government could not commit beyond the current period.

$q_2 = X_1 - q_1$.

In the absence of intertemporal commitment the optimal payment scheme also requires all firm types to exhaust the resource stock whenever θ^H is such that (13) is satisfied. Suppose that is the case. The optimal thing to do for the government is then to treat all firm types in the same way in period 2, by having them exhaust their remaining resource stock independently of their true θ_2. In that sense, there is in fact no incentive problem left for the government in period 2. As a result, the extraction paths will be the same under both symmetric and asymmetric information. Then and only then, whether or not the government can commit to future payment rules is of no consequence.[12]

Things are quite different if (13) does not hold. The firm then retains an information advantage in period 2 in the absence of intertemporal commitment by the government and the government faces an incentive problem in both periods. Under full commitment, however, as just explained, the firm looses its information advantage since at the beginning of the relationship it knows only the distribution of θ_2, which is common knowledge.[13] It is then in the interest of the government to shift production in favor of this second period as compared to the no commitment scenario.

If we continue to restrict attention to firm types for which the required first-period production is strictly interior when no intertemporal commitment is possible, then the government will do this by requiring all those firm types to produce a smaller quantity in period 1 and a compensating greater quantity in period 2. If we were to consider the firm types for which the optimal payment scheme requires corner solutions of the form $q_1 = X_1$ or $q_1 = 0$, then it would require fewer firm types to exhaust the resource in period 1 and more firm types to extract nothing in period 1 than it would if full commitment were not possible, and a smaller period 1 production of those firm types it wishes to choose an interior first-period production under full commitment.

3.3. Temporally correlated costs

When the privately observed cost is correlated over time, the multi-period agency relationship becomes more complicated. By revealing the period 1 cost parameter, the firm not only eliminates the uncertainty faced by the principal about the conditions of extraction in period 1, but also reduces the uncertainty about period 2 extraction, thus reducing its future informational advantage. Consequently the decision to reveal information, and the conditions inducing truthful revelation are more complex.

In fact a particular case of such situations gives rise to the well known ratchet effect, which occurs when the cost parameter is constant over time (so that revealing it in one period implies revealing it for all subsequent periods) and the principal is unable to commit beyond a single period. Such situations have been studied extensively when the only element that changes between periods is the private information variable, unlike the resource extraction relationship described in this article where the reserve stock provides an additional element of dynamics. Even in a two-period relationship, no separating equilibrium

[12]See Gaudet, Lasserre & Long (1991) for a detailed proof of this. The crucial assumption here is $p_2 \geq \theta^H + bX_1 + (1-\alpha)h(\theta^H)$, from which $p_2 \geq \theta^H + bX_1$ follows.

[13]Note that the possibility of full commitment resolves the second-period incentive problem whether or not all firms are required to exhaust. Therefore the qualitative comparison of the two optimal programs would be unchanged if we had $p_2 < \theta^H + bX_1$. The crucial factor is whether intertemporal commitment is possible or not.

exists in the repeated relationship, although in the static case full separation is feasible and desirable (see Laffont & Tirole 1993, Section 9.3). This result illustrates the more general fact that the revelation principle, as used in the previous two subsections, does not apply to repeated relationships in the absence of commitment.

Although this result strictly applies to (identically) repeated relationships and thus not to nonrenewable resource extraction, we are not aware of nonrenewable resource dynamic agency papers that use assumptions known to involve the ratchet effect in conventional repeated relationships. When their problem involves a time invariant private information variable, authors assume full commitment (Osmundsen 1998; Hung, Poudou & Thomas 2006) or restrict the number of types (Ing 2012).

Consider the case of full commitment. A well-known result applying to repeated relationships with commitment when the private information parameter is constant over time, is that the best that the principal can do is to commit to using the optimal short-term contract in each period. In other words, it is optimal for the principal to commit not to exploit the information obtained from the firm in previous periods.

With full intertemporal commitment and perfectly correlated costs, the resource owner is able to commit to a sequence $\{R_1(\tilde{\theta}_1), q_1(\tilde{\theta}_1);\ R_2(\tilde{\theta}_2, \tilde{\theta}_1), q_2(\tilde{\theta}_2, \tilde{\theta}_1)\}$ in our two-period nonrenewable resource model. Committing not to exploit the information obtained from the firm in period 1 would amount to offering a contract menu $\{R_1(\tilde{\theta}_1), q_1(\tilde{\theta}_1);\ R_2(\tilde{\theta}_2), q_2(\tilde{\theta}_2)\}$ designed using the same density and cumulative distributions for θ_1 and θ_2, despite the fact that no uncertainty on θ_2 remains if θ_1 is revealed.

It has not been proven that this is optimal when the short-run relationship is not repeated identically, as is the case with nonrenewable resources. Furthermore, when costs are perfectly correlated, it makes sense when intertemporal commitment is possible to treat the agency relationship as a one-shot contractual relationship, where the contract specifies output over several periods while information is sought and revealed only once, at the beginning of the relationship. Such a model is actually static from an informational point of view although it provides for the dynamics of resource extraction.

This is the approach taken by Osmundsen (1998), who investigates the effect of information asymmetry in initial reserves. In his two-period model, the remaining stock of reserves affects the cost of extraction, so that output does not directly reveal cost to the principal unless reserves are known. However, optimal output in any period implies some specific reserve level, so that, in order to pretend holding a particular amount of initial reserves, the firm must adapt its output in each period to the claim. An incentive compatible menu thus consists of one cumulative payment schedule and one production schedule for each period, designed according to the amount of initial reserves privately known to the firm at the beginning of the contractual relationship: $\{R(X_1), q_1(X_1), q_2(X_1)\}$. The role of reserves in extraction costs gives this model a Ricardian flavor, so that the Hotelling 'tilt' of production toward the present is not one of its features under full information. Consequently the result that the last period production is reduced under information asymmetry should not be interpreted as a reinforcement of the Hotelling 'tilt'. In fact production is reduced in both periods. Private information thus reduces both the pace, and the total amount, of production relative to the efficient solution. As usual in asymmetric information agency models, prescribing an inefficient output schedule relaxes the incentive constraints by making it more difficult for efficient (high reserves) types to mimic less efficient ones. This in turn allows the principal to abandon a lower proportion of the resource rent to the firm. Unlike Gaudet, Lasserre & Long (1995), Osmundsen does not find any exception to the traditional no-distortion at the top result. As we further explain in the next section, this is because the agency relationship is static from an informational point of view when initial reserves are the sole private information variable.

We have so far discussed only the case of perfect intertemporal correlation of types. Partial correlation is a much more difficult issue, that has not been addressed in dynamic agency problems involving natural resources specifically. Pavan, Segal & Toikka (2014) consider the design of incentive compatible mechanisms in a dynamic environment in which agents receive private information over time and decisions are made in multiple periods over an arbitrary time horizon. They show that 'as in static settings, distortions are introduced to reduce the agents' expected information rents, as computed at the time of contracting. However, because of the serial correlation of types, it is optimal to distort allocations not only in the initial period, but at every history at which the agent's type is responsive to his initial type' (p. 604). Clearly this applies to nonrenewable resources and illustrates the issues just described for the case of perfect correlation. The particular form that such distortions should take in resource extraction remains open to investigation.

4. The optimal terminal period

Under the assumption maintained so far that the relationship between the owner and the firm ends (optimally) in at most two periods, the only way to investigate whether the presence of asymmetry of information can result in the resource stock being exhausted later than it is under symmetric information is to consider situations where the resource stock is optimally exhausted in a single period under symmetric information. Conversely, if the resource stock is exhausted during the second period in the symmetric information benchmark case but is exhausted during the first period under asymmetric information, we have an acceleration. Gaudet, Lasserre & Long (1995) find that two cases may arise: either it remains optimal under asymmetric information for all firm types to exhaust the resource as assumed in the symmetric information benchmark; or the incentive contract prescribes some types not to exhaust the resource stock under asymmetric information. In the first case, fewer firms (if any) exhaust in the first period, and none exhaust earlier. Thus exhaustion is postponed if it is affected at all.

In the second case, where some firms abandon part of their resource stock at the end of the second period under information asymmetry, the prescription is for the most efficient firm types to extract more in the first period than in the symmetric benchmark. Some firm types that did not exhaust their reserves during the first period in the benchmark case may be asked to do so under asymmetric information. This means that exhaustion would be accelerated for these types. However, examples exhibiting the opposite effect may also be constructed.

The reason for this ambiguity lies in two factors that modify the optimal extraction rate in opposite directions under asymmetric information. The first factor is familiar and concerns all static adverse selection relationships. As illustrated on the left-hand side of (14), the marginal cost faced by the firm must be modified by the optimal payment scheme in order to satisfy incentive compatibility. The correction is a positive addition to marginal cost, $(1-\alpha)h(\theta_1)$, which calls for a reduction in output relative to the benchmark case. In the first case this factor is the sole modification arising from asymmetric information, so that exhaustion can only be delayed.

The second factor is specific to dynamic adverse selection relationships such as nonrenewable resource extraction. In the two-period version of the model, it arises only in the second case, when some firms abandon part of the resource stock in period 2 under asymmetric information. The opportunity cost of extracting the resource in period 1 rather than leaving it in the ground for future extraction is then lower than it was, ceteris paribus, under symmetric information. In other words the resource rent is now lower, which calls for higher period 1 production. This second factor may or may not dominate the incentive compatibility factor; it dominates it for sure for the most efficient types since the later is zero when $\theta = \theta^L$. Higher extraction in period 1 does not imply a change in the date of exhaustion. However, this may cause some types whose extraction rate was an interior solution in the benchmark case to be required to extract the totality of the reserve stock in period 1 under asymmetric information; for these firm types, the date of exhaustion is accelerated.

The effect of the asymmetry of information on the optimal terminal period is thus ambiguous in general in a two-period setup. It is nonetheless interesting to relax the assumption that the resource is worthless for $t = 3, 4, ...$ to analyze the effect of asymmetry of information on the duration of the agency relationship in a less constrained framework. In fact one might wonder whether the ambiguous effect just identified might be an incongruity arising from corner solutions that might disappear with additional flexibility in the time space. On the contrary it is found that the case where the lowest cost firm is left undistorted and the terminal date can only be increased under asymmetric information is in fact an artifice of the two-period case.

Gaudet, Lasserre & Long (1995, Section 5) analyze the three-period case in a way that can be generalized to any duration. Assuming that the optimal terminal date is 2 in the benchmark case, they analyze whether asymmetric information causes exhaustion to be postponed to period 3 or accelerated to period 1. They find that both are possible depending on firm type. A firm that draws an efficient type, say $\theta_1 = \theta^L$ in the first period may extract the totality of its reserve stock in that period under information asymmetry, while a firm that draws an inefficient type in period 1, and then perhaps again in period 2, may postpone exhaustion until period 3. This differentiation of types can be explained by the fact that the two corrections to marginal cost required under asymmetry of information are now present in period 1 and have different relative magnitudes according to firm type.

The incentive compatibility correction $(1-\alpha)h(\theta_1)$ increases the marginal cost of all types but θ^L. On the other hand, since the types to be drawn in periods 2 and 3 are unknown, it is certain that information asymmetry will introduce some inefficiency in the exploitation of reserves kept beyond period 1 for future extraction. The opportunity cost (the resource rent) of a unit of reserves is thus lower than under symmetry of information, which reduces the marginal cost; this is true whatever the type drawn in period 1, including θ^L. Consequently a firm of type $\theta_1 = \theta^L$ faces no incentive compatibility correction (since $h(\theta^L) = 0$) but faces a rent reduction: it will produce more in period 1 and possibly exhaust as soon as period 1 rather than exhausting in period 2 in the benchmark case. This is in contrast with static agency results where the best type is left undisturbed and where the distortions go in the direction of lower output.

The combined effect of the incentive compatibility cost correction and the rent reduction is likely to go in the opposite direction for inefficient types in period 1 because the term $(1-\alpha)h(\theta_1)$ is increasing in θ_1 so that it is likely to dominate the rent reduction at high values of θ_1. Firms that draw a high cost in period 1 will produce less, leave more reserves for the future, and may even end up exhausting in period 3 rather than in period 2 as in the benchmark case.

5. Other issues

We have concentrated our analysis so far to the application to nonrenewable resource regulation of the principal-agent problem with averse selection. In this section we wish to point out a few other issues relating to information asymmetry that we feel deserve more attention than they have received, if any.

One such issue relates to the source of information asymmetry. We have considered the important case where the source of asymmetry bears on the cost of extracting the nonrenewable resource. In some cases the firm may instead, or in addition, hold private information about its resource stock. To our knowledge, Osmundsen (1998) is the only one to consider a principal-agent problem with the *initial* resource stock as the source of information asymmetry. He assumes that the relationship between the principal and the agent lasts two periods and that the principal is able to commit for the two periods at the outset. Since the initial stock is obviously the same in both periods, we have a situation where the source of information asymmetry is in effect perfectly correlated over time: once the first-period stock is known, the stock remaining for the second-period follows directly from observing the first-period production and becomes common knowledge. The remaining stock is assumed to enter negatively as a parameter in the cost function and the parameters are chosen so that it is never optimal to exhaust the resource stock: the resource constraint is therefore never binding, so that no Hotelling-type rent is being generated. In terms of the notation used in the previous sections, this amounts to having $\theta_1 = \theta_2 = X_1$ as the cost parameter, where X_1 is the initial resource stock. As explained in Section 3.3, the problem is then static from an informational point of view. This is an interesting first approach to introducing the resource stock as the source of private information, but it leaves much room for further research in the truly dynamic framework inherent to the natural resource problem.

Another promising extension to the principal-agent framework described in Section 3 is to take into account the endogeneity of reserves. This can be done by introducing an exploration and development cost function, as is done in Gaudet & Lasserre (1988), Daubanes & Lasserre (2014) and Gaudet & Lasserre (2015). The stock of reserves is discovered and developed prior to being exploited, under technological and geological constraints such that the total cost increases with the amount of reserves that the firm chooses to develop. Clearly there is a lot of potential for the firm to acquire private information in that context. Yet the relationship between the government and the firm is also a long-term principal-agent relationship, as in many instances the principal will want to delegate exploration and development. Whether or not the same firm is responsible for both the exploration and development phase and the exploitation phase, the two phases must be viewed as connected. Indeed, since the proceeds from exploitation normally go toward financing exploration and development, the principal-agent relationship analyzed above for the extraction phase can be expected to be profoundly affected by the need for the principal to maintain proper incentives for expenditures in reserve exploration and development. The ability of the principal to commit is going to play a crucial role in that respect if the type of failure identified in other investment contexts is to be avoided (see Laffont & Tirole 1993, especially Sections 1.8 and 1.9).

There are also instances where private information about the resource stock raises important issues that do not present themselves as principal-agent problems. A case in point is the recent paper by Gerlach & Liski (2014). They model the strategic relationship between the seller of a nonrenewable resource, who has private information about the size of the resource stock it owns, and a buyer, who can at any time respond to the information generated through the market interaction by deciding to invest in a substitute, which amounts to a decision to sever the relationship after a given time-to-build delay. The result is a dynamic signalling game à la Spence (1973), but with inherent dynamics that arise because the resource stock gets depleted by consumption. The price announced by the seller is taken by the buyer as a signal as to the size of the remaining resource stock (the seller's type). After observing the signal, the buyer may choose to sever the relationship even before the resource stock is exhausted. The seller then has an incentive to overstate the resource stock so as to prolong the relationship. Sauré (2010) has also suggested a related signalling game to explain seemingly over-reporting of reserves by oil producers. In his case, the signal is associated to the resource stock as reported by the owner.

Our discussion has concentrated on nonrenewable resources, but asymmetry of information may also be a factor in the management of some renewable resources. This is a potentially fruitful area of research which remains largely unexplored. Forestry is a good example. The exploitation of the forest is usually delegated by the forest owner (often by a government) to a harvesting firm that may possess private information about the harvesting cost. In a recent paper, Tatoutchoup (2015) is the first to apply the principal-agent framework with adverse selection to characterize the optimal forestry contract under asymmetry of information about the harvesting cost. In that context, the objective of the owner is to choose an incentive mechanism that maximizes the present value of the forest — the trees and the land for replanting — taking into account the information constraints. The mechanism takes the form of a royalty scheme (a "stumpage fee") that will result in the harvesting firm choosing the rotation period (i.e. the age at which the trees are harvested and a new generation planted) that maximizes the owner's expected discounted revenue from the forest. The optimal incentive mechanism will generally require a departure from the first-best solution except for the lowest-cost type. In the case of forestry, the first-best, which holds for the symmetric information case, just as in the full information case, must satisfy the Faustmann rule (Faustmann 1849), in replacement of the Hotelling rule that characterized the first best in the case of nonrenewable resources. Tatoutchoup assumes that the principal can fully commit and looks at both the case where the cost parameter is perfectly correlated — hence the problem is essentially static from an informational point of view, the optimal contract being the same for all rotations — and the case of no temporal correlation, where the contract is history-dependent.

Finally, it is worth mentioning that the problem of designing incentive mechanisms under asymmetry of information can also arise when dealing with the control of pollution. For instance, the principal-agent framework with adverse selection can be of relevance for the design of environmental policy, as exemplified by a recent application to climate agreements by Helm & Wirl (2014). They consider a situation where there is multilateral externalities between the principal and the agent, who has private information about his valuation of climate damages. The problem can be viewed as that of designing an incentive mechanism whereby industrialized countries (the principal) can induce developing countries (the agent) to reveal their true valuation of damages. The mechanism takes the form of a contract in which both parties commit to binding emission targets.

The design of environmental policy can also raise important issues of moral hazard.

This is especially true of non-point source pollution — water or air pollution from diffuse sources. In those cases, although ambient pollution may be measured, the emissions (or abatement efforts) of individual polluters are not easily monitored. Each individual polluter can increase its profit by choosing a higher level of its unobservable pollution (i.e. lower level of unobservable abatement effort). Segerson (1988) and Xepapadeas (1991) have shown how the principal-agent framework can be used to design individualized incentive schemes to regulate pollution in such situations.[14]

6. Conclusion

Although asymmetric information in environmental and resource economics can sometimes be analyzed using a static framework, it is their inherently dynamic nature that makes resource issues notably distinct from many other economic problems. We have focused on such situations, particularly on principal-agent relationships with adverse selection arising in the exploitation of nonrenewable natural resources. There are two kinds of dynamic aspects to natural resource exploitation when information is incomplete. The first one is inherent to the capital theoretic nature of resources as the resource stock changes over time in the course of exploitation. The second one arises from the evolution of the information itself. Their combination creates situations and results not found in other contexts. Our purpose has been to provide an overview of how and why those particular situations and results occur. We have stressed the fact that the form taken by the optimal incentive mechanisms will depend on whether the principal is capable of long-term commitment or not, and whether the parameter that is subject to private information is temporally correlated or not.

While the literature on the theory of incentives under asymmetry of information is vast, its applications to natural resource issues remain surprisingly sparse. There is clearly room for further research. For nonrenewable resources this is particularly true of the complex situations involving temporally correlated private information, especially partially correlated private information. Reserve endogeneity is another neglected aspect of the management of nonrenewable resources under asymmetry of information. Several other interesting issues may also arise in the context of natural resource or environmental economics that deserve further work. We have mentioned renewable resources, some situations involving moral hazard, as well as interactions involving signalling. Hopefully this introductory review of the subject will arouse further interest in those issues.

LITERATURE CITED

Baron D. 1989. Design of regulatory mechanisms and institutions. In *Handbook of Industrial Organisation*, eds. R Schmalensee, R Willig. New York: North Holland, 1347–1447

Baron DP, Besanko D. 1984. Regulation and information in a continuing relationship. *Information Economics and Policy* 1:267–302

Cabe R, Herriges JH. 1992. The regulation of non-point-source pollution under imperfect and asymmetric information. *Journal of Environmental Economics and Management* 22:134–146

Dasgupta P, Hammond P, Maskin E. 1979. The implementation of social choice rules: some results on incentive compatibility. *Review of Economic Studies* 46:185–216

[14]See also Cabe & Herriges (1992) and Segerson & Wu (2006) for interesting analyses of the design of non-point-source pollution control under asymmetry of information with moral hazard.

Daubanes J, Lasserre P. 2014. Dispatching after producing: The supply of non-renewable resources. CIRANO Working Paper 2014s-42, Montreal

Faustmann M. 1849. Berechnung des werthes, welchen waldboden, sowie noch nicht haubare holzbestände für die waldwirtschaft besitzen. *Allgemeine Forst-und Jagd-Zeitung* 15:441–455. Translated into English by W. Linnard under the title "On the determination of the value which forest land and immature stands possess for forestry", in M. Gane, ed., *Martin Faustmann and the evolution of discounted cash flow*, Oxford: Commonwealth Forestry Institute, Institute paper no. 42, 1968, pp. 27–55.

Gaudet G, Lasserre P. 1988. On comparing monopoly and competition in exhaustible resource exploitation. *Journal of Environmental Economcis and Management* 15:412–418

Gaudet G, Lasserre P. 2015. The taxation of nonrenewable natural resources. In *Handbook on the Economics of Natural Resources*, eds. R Halvorsen, D Layton. Cheltenham, U.K.: Edward Elgar Publ. In press

Gaudet G, Lasserre P, Long NV. 1991. Optimal resource royalties with unknown and temporally independent extraction cost structures. Cahier de recherche No. 66, CERPE, Université du Québec à Montréal

Gaudet G, Lasserre P, Long NV. 1995. Optimal resource royalties with unknown and temporally independent extraction cost structures. *International Economic Review* 36:715–749

Gerlach R, Liski M. 2014. Cake-eating with private information. CESifo Working Paper No. 5050

Helm C, Wirl F. 2014. The principal-agent model with multi-lateral externalities: An application to climate agreements. *Journal of Environmental Economics and Management* 67:141–154

Hotelling H. 1931. The economics of exhaustible resources. *Journal of Political Economy* 39:137–175

Hung NM, Poudou JC, Thomas L. 2006. Optimal resource extraction contract with adverse selection. *Resources Policy* 31:78–85

Ing J. 2012. The impact of commitment on nonrenewable resources management with asymmetric information on costs. WP 1205, GATE Lyon-St Étienne

Laffont JJ, Martimort D. 2002. The theory of incentives: The principal-agent model. Princeton, New Jersey: Princeton University Press

Laffont JJ, Tirole J. 1988. The dynamics of incentive contracts. *Econometrica* :1153–1175

Laffont JJ, Tirole J. 1993. A theory of incentives in procurement and regulation. Cambridge, Mass.: MIT Press

Myerson R. 1979. Incentive-compatibility and the bargaining problem. *Econometrica* 47:61–73

Osmundsen P. 1998. Dynamic taxation of non-renewable natural resources under asymmetric information about reserves. *Canadian Journal of Economics* 31:933–951

Pavan A, Segal I, Toikka J. 2014. Dynamic mechanism design: a Myerson approach. *Econometrica* 82:601–653

Salanié B. 1997. The economics of contracts: A primer. Cambridge, Mass.: MIT Press

Sauré P. 2010. Overreporting oil reserves. Swiss National Bank Working Papers 2010-7

Segerson K. 1988. Uncertainty and incentives for nonpoint pollution control. *Journal of Environmental Economics and Management* 15:87–98

Segerson K, Wu J. 2006. Nonpoint pollution control: Inducing first-best outcomes through the use of threats. *Journal of Environmental Economics and Management* 51:165–184

Spence M. 1973. Job market signaling. *Quarterly Journal of Economics* 90:225–243

Tatoutchoup D. 2015. Optimal forestry contracts under asymmetry of information. *Scandinavian Journal of Economics* In press

Xepapadeas AP. 1991. Environmental policy under imperfect information: Incentives and moral hazard. *Journal of Environmental Economics and Management* 20:113–126

1130, rue Sherbrooke Ouest, bureau 1400, Montréal (Québec) H3A 2M8
Tél. : 514-985-4000 • Téléc. : 514-985-4039
www.cirano.qc.ca • info@cirano.qc.ca