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Technology Adoption in Nonrenewable Resource Management

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RESUMEN

La escasez de los recursos no renovables es una preocupación habitual al construir modelos de crecimiento óptimo. El cambio tecnológico desempeña un importante papel en esos modelos puesto que se supone que su presencia mitiga los efectos del agotamiento de los recursos en las sendas temporales de extracción. En este trabajo formalizamos el problema genérico de una empresa competitiva que extrae un recurso no renovable, para analizar las políticas óptimas de extracción y adopción de tecnología cuando la adopción es costosa, en un contexto determinista y estocástico, tanto si la firma anticipa la adopción como si no. Usando una función de costes de extracción cuadrática, nuestros resultados no apoyan la opinión habitual según la cual la empresa sólo incurrirá en el coste de adopción cuando el stock está lo suficientemente agotado.

Palabras clave: recursos no renovables; adopción de tecnología; efecto agotamiento; coste de adopción.

ABSTRACT

Nonrenewable resource scarcity has been a traditional concern when designing optimal growth models. Technological change has played an important role in those models, since its presence is assumed to mitigate the depletion effect on extraction paths over time. We formalize the general problem of a competitive nonrenewable resource extracting firm to analyze optimal extraction behavior and technology adoption when adoption is costly, both in a deterministic and a stochastic environment, when the firm either anticipates adoption or not. Based on a quadratic extraction cost function, our results do not support the traditional view according to which the firm will only incur in an adoption cost when the stock is depleted enough.

Keywords: nonrenewable resources; technology adoption; depletion effect; cost of adoption.

JEL classification: O33, Q65

1 Introduction

Simple models of nonrenewable resource extraction consider the case of a firm that has a fixed production process, implying that the firm's cost function does not change throughout the entire period of extraction activities. However, the assumption of no technical improvements in production is empirically inappropriate for most resources. Nonrenewable resource scarcity has been a traditional concern when designing optimal growth models. The presence of an underlying process of exogenous technological development has played an important role in those models, since, according to them, its presence mitigates the depletion effect on extraction paths over time. In fact, empirical research shows that the role played by technology in the natural resource industry has been crucial. In particular, Simpson [14] examines the impact of technological change for several natural resource industries in the US, and concludes that "...costs of production have not increased because the inevitable effects of depletion have, to date, been more than offset by improvements in technology." [14, pg. 2][1] Recently, Managi, Opaluch, Jin and Grigalunas [11] have measured depletion effects and technological change for offshore oil production in the Gulf of Mexico based on a unique field-level data set from 1947-1998. This study also supports the hypothesis

[1] See Tilton and Landsberg[15], as well as Krautkraemer[9] and Dasgupta[3].

that technological progress has mitigated depletion effects over the study period. Moreover, among the different components of technological change, these authors show that diffusion had a significantly larger impact on total factor productivity than technological innovation. More generally, Hall and Khan [8] argue that it is diffusion rather than invention or innovation that ultimately determines the pace of economic growth and the rate of change of productivity.

Furthermore, in the context of nonrenewable resources, as suggested by Lundstrom [10], two types of technologival innovation can be distinguished: incremental and drastic. While incremental innovations increase the efficiency of extraction and discovery of already familiar resource stocks, increasing the rate of exhaustion, drastic innovations are revolutionary, in the sense that they increase the quantity of familiar resource stocks, either by introducing an unexpected technology or by adding to the number of familiar resources.

In contrast to many studies in the literature in which the potential of technology improvements to mitigate resource scarcity is examined as an empirical issue, we model the firm's optimal decisions both on resource extraction and on adoption of an incremental innovation. Either the new technology is unanticipated by the firm, or the firm anticipates the possibility of adoption along the exploitation program. We examine decisions on optimal extraction and optimal adoption by a competitive firm, both in a deterministic and a stochastic environment.[2]

The typical model of adoption is characterized by potential adopters contemplating the use of a technology that reduces the marginal cost of production but has a known adoption cost. Adoption will only occur if its net benefits are positive. If the possibility of adoption was unanticipated, a boundary separating the adoption from the non-adoption region can be defined. The characteristics of this boundary as well as the location of the two regions are obtained as part

[2] The problem of choosing the timing of adoption was examined for a competitive firm in the context of the investment literature, as in Balcer and Lippman [1]. Recently, Doraszelski [5] improves upon Balcer and Lippman[1] by distinguishing between innovations and improvements. Also, it extends Farzin, Huisman and Kort' paper [7] by building upon the idea that the occurrence of the next improvement depends on the time elapsed since the previous innovation. However, the presence of a nonrenewable resource stock changes the dynamics of the problem, as the firm has to decide simultaneously at each time period how much to extract and whether to adopt or not. This is also different from Pindyck's [12].

of the solution to the firm's problem. To account for the simultaneous choice of optimal extraction at each time period and the optimal timing of adoption, the case in which the firm anticipates the possibility of adoption is illustrated by solving numerically a three-time horizon dynamic programming problem.

For a quadratic extraction cost function, we show that the main driving force of adoption is the possibility of taking advantage of lower costs. For firms with more depleted stock levels at the time the new technology becomes available, the technological opportunities can only be applied to a smaller amount of the stock, reducing benefits from adoption. Firms with more depleted stocks may choose not to adopt if prices are low enough. When the firm anticipates technological improvements it acts strategically by reducing extraction in the first period in order to save resource for the future, when it can take advantage of the lower extraction costs. When facing uncertainty about the benefits from adoption, the firm may wait rather than adopting immediately, which implies that the adoption decision will be delayed. This could never be captured if the firm does not anticipate adoption. Finally, our results can be contrasted to those in Pindyck [12], where exploration or development of already familiar resource stocks can be seen as an alternative to adoption.

It is often stated in empirical work that the firm will only incur into a cost of adoption when the stock is depleted enough. Consequently, one would expect adoption to occur only for those firms whose resource stock was already severely depleted at the time the technology upgrading becomes available. Our findings are in contrast to this view, in what concerns both the decision to adopt and the intensity of adoption. Our results clarify the importance of modeling the firm's decision problem, contributing to a more thorough understanding of the role of technology improvements on mitigating depletion on nonrenewable resource management.

The remainder of the paper is organized as follows. In Section 2, the general problem of the firm with unanticipated technological improvements and volatile prices is described. In Section 3, additional structure is imposed into the problem by specifying a quadratic cost function. The competitive firm's problem is then solved, both in a deterministic and a stochastic environment, in two cases reflecting different costs of adoption. Section 4 examines the firm's problem when technological improvements are anticipated. Finally, the main conclusions of the paper are summarized in Section 5.

2 The Firm's Problem

In this section, a general model of a competitive nonrenewable resource extracting firm is used to analyze optimal extraction behavior and optimal technology adoption of an incremental type, assuming that the availability of the new technology was unanticipated by the firm.

Without the possibility of adoption, the firm's problem consists of choosing the extraction path to maximize the expected present value of profits over time, given the evolution for market prices and the stock, as follows:

$$V(S_0, p_0; a_0) = \underset{\{e_t\}}{Max}\ E_0 \left[\int_0^\infty \left[p_t e_t - C(e_t, S_t; a_0)\right] e^{-rt} dt \right] \quad (1)$$

$$s.t.$$

$$dS_t = -e_t dt \quad (2)$$

$$S_0 = \overline{S} \quad (3)$$

$$S_t \geq 0; \quad e_t \geq 0 \quad (4)$$

$$dp_t = \mu p_t dt + \sigma_p p_t dw_p \quad (5)$$

The transversality conditions for the stock are given by

$$\lim_{t \to \infty} E_t(V_{S_t}) \exp(-rt) \geq 0, \qquad \lim_{t \to \infty} E_t(V_{S_t}) \exp(-rt) S_t = 0.$$

where V_{S_t} represents the marginal user cost of the resource stock at t.

The optimal value function at time t, $V(S_t, p_t; a_0)$, represents the expected present value of the profits obtained from the extraction program operating with an (unchanged) technology level a_0. Moreover, S_t is the existing stock of resource at time t, p_t is the market price of the resource at time t, e_t is extraction at t, $\overline{S}$ is the known endowment of resource stock available to the firm, and a_0 represents the quality of technology at $t = 0$, and for the whole program.

From the point of view of the firm, prices are exogenous. However, it is assumed that there is uncertainty surrounding the evolution of market resource prices over time. This uncertainty is driven by a one-dimensional Brownian motion w_p, as described in equation (4), where σ_p is the volatility of market prices.

Moreover, the extraction cost function is assumed to have the following properties (all derivatives evaluated at t):

1. twice continuously differentiable; $C(e, S; a) < \infty$, for all e, S, given a.

2. strongly jointly convex in (e, S): the principal minors of order one, two, and three are strictly positive;

3. according to intuition, it is expected that $\frac{\partial C}{\partial e} > 0$, $\frac{\partial C}{\partial S} < 0$, $\frac{\partial C}{\partial a} < 0$, $\frac{\partial^2 C}{\partial a^2} > 0$, $\frac{\partial^2 C}{\partial S^2} > 0$, $\frac{\partial^2 C}{\partial e \partial S} < 0$, $\frac{\partial^2 C}{\partial S \partial a} > 0$, $\frac{\partial^2 C}{\partial e \partial a} < 0$.

   Thus, marginal extraction cost is positive and increasing (reflecting diminishing returns to extraction); there are stock effects in both total and marginal cost; as for technology a, it is assumed to lower total and marginal extraction cost, and to decrease the impact of stock effects on total cost (note that $\frac{\partial C}{\partial S}$ becomes smaller in absolute value when a increases).[3]

2.1 Solution to Firm's Problem

In this subsection, we describe the solution of problem (1), that is, the solution to the firm's problem without adoption. This problem satisfies the associated Bellman equation, as follows:

$$rV = \underset{e}{Max}\left[pe - C(e, S; a_0) - V_S e + \mu p V_p + \frac{1}{2} V_{pp} \sigma_p^2 p^2\right] \quad (6)$$

If the right-hand side has an interior maximum, then e that satisfies the above partial differential equation must satisfy the Maximum Principle and

$$p - \frac{\partial C}{\partial e} = V_S, \quad (7)$$

[3] These assumptions are equivalent to those found in the literature. See, for example, Farzin [6], or Krautkraemer [11]. We also assume that if nonextractive net benefits exist they are not reduced by an increase in the level of the stock, and that there are strictly positive net benefits from extracting the first unit of the resource.

where V_S is the expected marginal user cost of the resource. Equation (7) yields the optimal policy function for extraction, $e^*(S, p, V_S; a_0)$, so that, evaluated at the optimum, equation (6) can be written as:

$$\begin{aligned} rV &= -C(e^*(S,p,V_S;a_0),S;a_0) + \frac{\partial C(e^*(S,p,V_S;a_0),S;a_0)}{\partial e} \\ & e^*(S,p,V_S;a_0) + \mu p V_p + \frac{1}{2} V_{pp}\sigma_p^2 p^2 \end{aligned} \quad (8)$$

Thus, the solution $V(.)$ depends on the stock of the resource as well as on prices, for a given quality level a.

Using Itô's Lemma and by some manipulations, since $V_{Sp} = 1$ from condition (7), the expected rate of change in the opportunity cost of the resource can be stated as:

$$\frac{1}{dt} EdV_S = rV_S + \frac{\partial C}{\partial S} + \sigma_p^2 p^2 \quad (9)$$

which is the portfolio balancing equation in the stochastic context. The last term accounts for the marginal expected cost due to the volatility of market prices. This term contributes positively to the expected change in the opportunity cost, in contrast to the depletion effect.

2.1.1 The adoption decision

In this section, the conditions under which the firm chooses whether to adopt or not, at the time a new technology becomes available, $t = \tau$, are examined. The firm may either keep its present technology, or adopt a new one at a cost. Unless the firm chooses to adopt a new technology, a does not change. When adopting a more advanced technology at time $t = \tau$, the quality increases according to

$$a_{\tau^+} = (1 + \upsilon_\tau) a_{\tau^-} \quad (10)$$

At $t = \tau$, the upgrading rate, $\upsilon_\tau > 0$, may be a choice variable of the firm. The general cost incurred by the firm when it decides to adopt, $c(a_{\tau^-}, \upsilon_\tau, z)$, may depend on different variables, such as the quality level at the time it becomes available, a_{τ^-}, the upgrading rate, υ_τ, or others, represented by z.

For the case of unanticipated technological improvements, the firm's problem can be solved as if there was a single technological improvement. Thus, at $t = \tau$, $a_{\tau^+} = a_\tau$ and $a_{\tau^-} = a_0$, the firm decides to adopt at $t = \tau$ if the present value of expected profits adopting are at least the present value of expected profits from adopting, that is, as long as

$$-V(S_\tau, p_\tau; a_0) - c(a_0, \upsilon_\tau, z) + V(S_\tau, p_\tau; a_\tau) \geq 0 \tag{11}$$

where $V(S_\tau, p_\tau; a_0)$ represents the value function at $t = \tau$ with unchanged quality a_0 (no adoption) for $\tau < t \leq \infty$, and $V(S_\tau, p_\tau; a_\tau)$ gives the maximum expected value of profits at $t = \tau$ obtained from the extraction program operating with an upgraded technology of quality a_τ for $\tau \leq t \leq \infty$. In other words, $V(S_\tau, p_\tau; a_\tau)$ is the solution of the following problem:

$$V(S_\tau, p_\tau; a_\tau) = \underset{\{e_t\}}{Max}\ E_\tau \left[\ \int_\tau^\infty \left[p_t e_t - C(e_t, S_t; a_\tau)\right] e^{-r(t-\tau)} dt\ \right]$$

subject to the same constraints as in (1), where $a_\tau = (1 + \upsilon_\tau)a_0$.

It is possible to derive and characterize a boundary that separates the adoption region from the non-adoption one. The exact location of these two regions with respect to this boundary depends upon the behavior of the benefit of adoption with respect to the stock and to prices, respectively, in the neighborhood of the boundary. From (11), the boundary is given by

$$V(S_\tau, p_\tau; a_0) + c(a_\tau, \upsilon_\tau, z) = V(S_\tau, p_\tau; (1 + \upsilon_\tau)a_0) \tag{12}$$

If the left-hand side of (12) is larger than the right-hand side, then the firm does not adopt, and adopts otherwise. Moreover, if υ_τ is also a choice of the firm, condition (12) has to hold at $\upsilon_\tau = \upsilon_\tau^*$, which represents the optimal level of the upgrading rate, that is, is the level of υ_τ that maximizes the left-hand side of (11) with respect to the upgrading rate at $t = \tau$, υ_τ. This condition is similar to the value matching condition in optimal stopping problems.[4]

3 Solution to Firm's Problem with Quadratic Costs

In this section, additional structure is imposed into the above adoption problem for tractability reasons, namely by using specific functional forms for extraction

[4] See Dixit and Pindyck [4].

and adoption costs. The extraction cost function is assumed to be quadratic in extraction and stock, as follows:

$$C(e_t, S_t; a_t) = \frac{1}{a_t}\left[\alpha_1 e_t^2 + \alpha_2 S_t^2 + \alpha_3 e_t S_t\right] \tag{13}$$

To ensure that the extraction cost function has the desirable properties, it is required that $\alpha_1 > 0$, $\alpha_2 > 0$, $\alpha_3 < 0$, $2\alpha_1 e + \alpha_3 S > 0$, $-\alpha_3 e - 2\alpha_2 S > 0$, and $\alpha_3^2 > 4\alpha_2\alpha_1$.

Two cases are considered corresponding to two different adoption costs. In Case 1, the cost of adoption is exogenous to the firm and is given by $(ca_0 + k)$. That is, the cost incurred by the firm depends on the current quality level, a_0, besides a fixed cost, $k > 0$. As the cost of adoption does not depend on the upgrading rate, it is optimal for the firm to upgrade as much as possible. Thus, we assume that the upgrading rate is fixed at some maximum level υ. In contrast, Case 2 considers the adoption cost given by $(c\upsilon + k)$. Now the cost of adoption depends on the upgrading rate, υ, or the intensity of adoption, so this variable will also be a decision variable of the firm.

3.1 Deterministic prices

Before considering volatile prices, it is instructive to begin with an examination of the deterministic case, in which the evolution of market resource prices over time is given by $dp_t = \mu p_t dt$, where $\mu > 0$ or $\mu < 0$.[5]

Equation (8) can be restated as follows:

$$\begin{aligned} rV \quad = \quad & \frac{a_0(p - V_S)^2}{2\alpha_1} - \frac{S\alpha_3(p - V_S)}{2\alpha_1} - \frac{\left[a_0(p - V_S) - S\alpha_3\right]^2}{4\alpha_1 a_0} - \frac{\alpha_2}{a_0}S^2 - \\ & - \frac{S\alpha_3 a_0(p - V_S) - S^2\alpha_3^2}{2\alpha_1 a_0} + \mu p V_p, \end{aligned} \tag{14}$$

where, from first order condition (7) and assuming an interior solution, optimal extraction is given by

$$e^*(p, S, V_S) = \frac{a_0(p - V_S) - S\alpha_3}{2\alpha_1}. \tag{15}$$

In order to solve equation (14) for $V(p, S; a)$ we use the following guess:

$$V(p, S; a_0) = \beta_1 p^2 + \beta_2 S^2 + \beta_4 Sp + \beta_7 p + \beta_9 S + \beta_{10} \tag{16}$$

[5] The satisfaction of the transversality conditions for the stock is shown in the Appendix.

which is the only solution of the problem.[6]

The solution is given by:

$$V(p,S;a_0) = -\frac{1}{4}a_0\upsilon\frac{(r-\mu)^2}{\Delta}p^2 + \frac{\rho}{a_0}S^2 + \frac{2\rho+\alpha_3}{2\rho-2r\alpha_1+\alpha_3+2\mu\alpha_1}Sp \tag{17}$$

where

$$\begin{aligned}\Delta &= -r^3\alpha_1 + 2\mu\alpha_1 + r^2\rho + r^2\alpha_3 - 4r\mu\rho + 4r^2\alpha_1\mu - \\ &\quad -3r\mu\alpha_3 - 5r\alpha_1\mu + 4\mu\rho + 2\mu\alpha_3 - r\alpha_2 + 2\mu\alpha_2,\end{aligned} \tag{18}$$

and

$$\rho = \frac{+4r\alpha_1 - 4\alpha_3}{8} \pm \sqrt[2]{\frac{(-4r\alpha_1+4\alpha_3)^2 - 16(-4\alpha_2\alpha_1+\alpha_3^2)}{8}}. \tag{19}$$

It is useful to look separately at $r=\mu$, and $r>\mu$.[7]

3.1.1 Case 1: constant marginal cost of adoption

When $r=\mu$, at $t=\tau$, from equation (17), the firm compares profits just before and immediately after the eventual adoption, as follows

$$-\frac{\rho\upsilon}{a_0(1+\upsilon)}S^2 - ca_0 - k = 0. \tag{20}$$

Equation (20) represents the boundary that separates the adoption from the non adoption region. It gives a threshold value for the stock, $S^* = \sqrt[2]{-\frac{(ca_0+k)a_0(1+\upsilon)}{\rho\upsilon}}$, according to which the firm decides whether to adopt ot not at $t=\tau$. This threshold value represents the boundary that separates the adoption region from the non-adoption one, and is independent of prices, given a_0 and υ. The exact location of these two regions relative to the boundary depends on how the benefit of adoption behaves with respect to the stock, and to prices.

To determine how benefits of adoption change with respect to the stock, we differentiate (20):

$$\frac{-2\upsilon\rho S}{a_0(1+\upsilon)} \tag{21}$$

[6] We use the indeterminate coefficients method to obtain expressions for the coefficients of the value function, in terms of the coefficients of the cost function. See Bertsekas [2].

[7] The case in which $r<\mu$ is excluded, as there will be an incentive to hoard unlimited quantities of the resource, and the market would not clear.

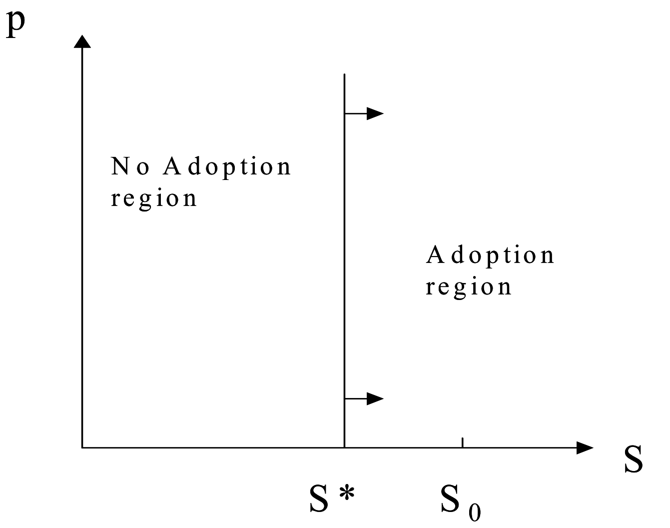

Figure 1: Adoption and Non-adoption Regions $r = \mu$

For $S > 0$, it is increasing in the level of the stock, since $\rho < 0$. [8] Therefore, for any stock level S_τ such that $S^* \leq S_\tau$, the firm will adopt a new technology, and vice-versa for $S_\tau < S^*$.

The derivative of (20) with respect to prices is always zero when $r = \mu$ and does not depend on the stock. Note that the threshold value S^* is larger for firms with better technology. Thus, independently of price behavior, the adoption region shrinks for higher a_0. Figure 1 illustrates these results.

When $r > \mu$, the threshold condition is now given by

$$-\frac{a_0 \upsilon^2 (r-\mu)^2}{4\Delta} p^2 - \frac{\rho \upsilon}{a_0(1+\upsilon)} S^2 - c a_0 - k = 0, \qquad (22)$$

where Δ is as defined before. Differently from when $r = \mu$, expression (22) depends both on the level of the stock, S, and on price, p, although the derivative condition for the stock is the same as before. Thus, the boundary between the adoption region and the non-adoption one is defined by a relationship between S and p.

[8] From equation (13) and Appendix A, the marginal cost of extraction is $\frac{\partial C}{\partial e} = -2\rho \frac{S}{a_0}$, which is positive iff $\rho < 0$, so that only the negative root of (19) is feasible.

The behavior of the boundary can be obtained from equation (22). As $\rho < 0$,[9] it will depend on the sign of Δ, which is assumed to be negative in order to have a well-defined problem.[10] Given $\Delta < 0$, we can find pairs (p^{**}, S^{**}) for which condition (22) is satisfied, representing the boundary that separates the adoption region from the non-adoption one. In this case, the boundary is quadratic and concave. This originates one adoption region and one non-adoption one.

From (22), we obtain the intercepts both in the horizontal and in the vertical axis. The intercept in the horizontal axis is given by

$$S^{+} = \sqrt[2]{\frac{-(ca_0 + k)a_0(1+\upsilon)}{\rho\upsilon}}, \tag{23}$$

while the intercept in the vertical axis is

$$p^{+} = \sqrt[2]{\frac{-4(ca_0 + k)\Delta}{a_0\upsilon^2(r-\mu)^2}}. \tag{24}$$

To identify the adoption region and the non-adoption one we make use of two derivative conditions.

Now, the sign of the derivative of the net benefit of adoption, given by the left-hand side of equation (22) with respect to price, is given by

$$-\frac{1}{2}a_0\upsilon^2\frac{(r-\mu)^2}{\Delta}p. \tag{25}$$

As $\Delta < 0$, whether prices are increasing or decreasing, condition (25) is unambiguously positive for feasible values of the parameters.[11] Note that an increase in the price always increases the net benefit of an increase in the technology level.

Since the derivative condition with respect to the stock is again given by expression (21), these results imply that the adoption region is located to the

[9] For the marginal extraction cost calculated along the optimal extraction path, that is, $\frac{\partial C(e^*)}{\partial e} = \frac{1}{a_0}\left[-2\frac{-2S\rho^2 - S\rho\alpha_4 + 2S\rho\alpha_1 r - 2S\rho\alpha_1\mu - a_0p\alpha_1 r + a_0p\alpha_1\mu}{-2\rho - \alpha_4 + 2\alpha_1 r - 2\alpha_1\mu}\right]$ to be positive when $r > \mu$, it has to be the case that $\rho < 0$, which implies that only the negative root of (19) is feasible.

[10] The cases in which $\Delta > 0$ are not considered since the intercepts in the vertical axis are complex numbers, and the boundary is not well defined.

[11] When $\mu > 0$, and prices are increasing over time, condition (25) could be negative, for $\Delta > 0$.

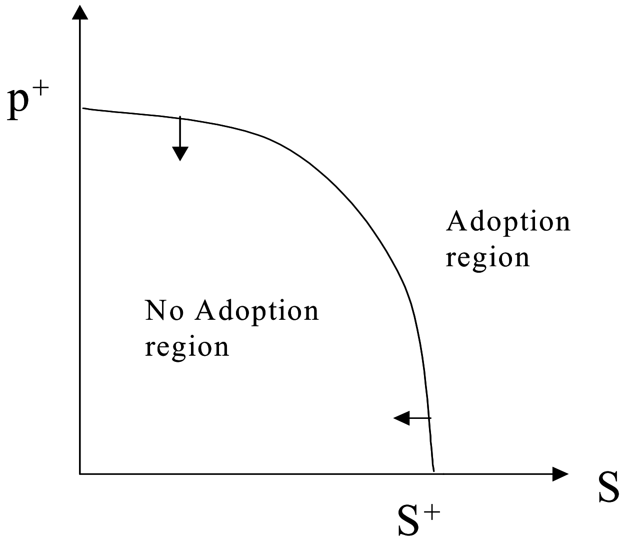

Figure 2: Adoption and Non-adoption Regions $r > \mu$

right of the boundary and the non-adoption one to the left. Therefore, prices are crucial to whether the firm chooses to adopt or not, as illustrated in Figure 2. As before, the larger the stock remaining at $t = \tau$, the larger the net benefit from adoption. Moreover, the higher the price at $t = \tau$, the larger the benefit from adoption.

For a given r, the impact of a change in μ on both the slope of the boundary and the intercept p^+ depends on the sign of $\frac{\partial\Delta}{\partial\mu}$. If $\frac{\partial\Delta}{\partial\mu} < 0$, the higher the price drift the steeper the boundary, implying that prices are less relevant for the adoption choice decision. In the limit case, we are back in the case $r = \mu$. Therefore, the non-adoption region shrinks as μ decreases.[12] Moreover, the boundary is different between firms, depending upon the quality level operated by each firm at $t = \tau$. In particular, p^+ is lower and S^+ is higher for larger a_0.[13]

By inspection of Fig. 2, we can observe that the adoption decision depends on the exact location of the initial price and stock. It also depends on the price

[12] If $\frac{\partial\Delta}{\partial\mu} > 0$, the result is ambiguous.

[13] If $\frac{\partial\Delta}{\partial\mu} < 0$, the stock level is less relevant for the adoption decision at $t = \tau$ the lower is μ and the higher is a_0.

drift μ relative to the discount rate r, given the value of all the other parameters. Therefore, we conclude that:

(a) when $S_\tau > S^+$, the firm will decide to adopt, independently of prices;

(b) when $S_\tau < S^+$, the decision to adopt depends on the price, namely, when prices are high enough at $t = \tau$, the firm will decide to adopt, while when prices are low enough, the firm will decide not to adopt.

In this problem, as adoption reduces marginal extraction costs, and the eventual adoption at $t = \tau$ is unanticipated by the firm, the major force influencing adoption behavior is the possibility of taking advantage of lower costs. Therefore, the benefits from adoption increase with the resource stock remaining at $t = \tau$. In fact, for firms with more depleted stock levels, the technological opportunities can only be applied to a smaller amount of the stock, reducing net benefits from adoption. As it is clear from the previous analysis, in order to be optimal for a firm with a low stock level to choose adoption, prices have to be high enough.

These results suggest that not only firms with depleted stocks will adopt. Instead, we have shown that firms with large stocks are more likely to adopt, independently of the price level, while firms with small stocks may choose not to adopt if prices are low enough at $t = \tau$.

3.1.2 Case 2: cost depends on the upgrading rate

In order to better understand the role played by prices and stock levels in the adoption decision, the relationship between the intensity of the technological upgrading, that is, the level of the upgrading rate, υ, and those variables is examined. To this end, we consider a second case in which adoption costs depend on the level of the upgrading rate, $(c\upsilon + k)$, rather than on the technology level a_0 (Case 1), besides the fixed cost, k, as before.

When $r = \mu$, the condition for the firm to decide whether to adopt at $t = \tau$ is given by

$$-\frac{\rho\upsilon}{a_0(1+\upsilon)}S^2 - c\upsilon - k = 0. \tag{26}$$

The optimal level of the upgrading rate, υ^*, is obtained by maximizing the left-hand side of (26) with respect to υ, that is, by maximizing the net benefits from adoption,

$$\upsilon^* = S\sqrt[2]{\frac{-\rho}{ca_0}} - 1,$$

as strict concavity is guaranteed. The two derivative conditions with respect to the stock and prices, respectively, that were derived for Case 1 still apply, except that now the upgrading rate is evaluated at υ^*. Since $\frac{\partial \upsilon^*}{\partial S} = \sqrt[2]{\frac{-\rho}{ca_0}}$ is always positive, firms with larger stocks at $t = \tau$ will optimally choose a larger upgrading rate.

When $r > \mu$, the condition for the firm to choose adoption is given by

$$-\frac{a_0\upsilon^2(r-\mu)^2}{4\Delta}p^2 - \frac{\rho\upsilon}{a_0(1+\upsilon)}S^2 - c\upsilon - k = 0. \tag{27}$$

As before, the optimal level of the upgrading rate υ^* is obtained by maximizing the left-hand side of (27) with respect to υ.

By totally differentiating the first-order conditions with respect to υ and evaluating them at υ^*, and using the Implicit Function Theorem, we obtain

$$\frac{d\upsilon^*}{dS} = \frac{\frac{2\rho}{a_0(1+\upsilon)^2}S}{-\frac{a_0(r-\mu)^2}{2\Delta}p^2 + \frac{\rho}{a_0(1+\upsilon)^3}S^2} \tag{28}$$

$$\frac{d\upsilon^*}{dp} = \frac{\frac{a_0\upsilon(r-\mu)^2}{\Delta}p}{-\frac{a_0(r-\mu)^2}{2\Delta}p^2 + \frac{\rho}{a_0(1+\upsilon)^3}S^2}. \tag{29}$$

The second-order condition for a maximum requires that the denominator in both (28) and (29) is negative, reflecting the fact that the marginal benefit of the intensity of adoption decreases with the level of the upgrading rate. Hence, the intensity of adoption increases with the level of the resource stock, as well as with prices at $t = \tau$.

3.2 Volatile prices

The results presented in this subsection are for the case of constant marginal costs of adoption (Case 1). When facing volatile prices, the firm's problem is given by (1), and satisfies the following partial differential equation:

$$\begin{aligned} rV &= \frac{a_0(p-V_S)^2}{2\alpha_1} - \frac{S\alpha_3(p-V_S)}{2\alpha_1} - \frac{\left[a_0(p-V_S) - S\alpha_3\right]^2}{4\alpha_1 a_0} - \frac{\alpha_2}{a_0}S^2 - \\ &\quad -\frac{S\alpha_3 a_0(p-V_S) - S^2\alpha_3^2}{2\alpha_1 a_0} + \mu p V_p + \frac{1}{2}V_{pp}\sigma_p^2 p^2, \end{aligned} \tag{30}$$

after substituting the optimal extraction for an interior solution.

We use the indeterminate coefficients method to obtain expressions for the coefficients of the value function, in terms of the coefficients of the cost function, as before. The solution is given by:

$$V(p,S;a_0) = -\frac{1}{4}a_0\upsilon\frac{(r-\mu)^2}{\Delta+\sigma^2\Psi}p^2 + \frac{\rho}{a_0}S^2 + \frac{2\rho+\alpha_3}{2\rho-2r\alpha_1+\alpha_3+2\mu\alpha_1}Sp \quad (31)$$

where

$$\begin{aligned}\Gamma &= \Delta+\sigma^2(-\rho r+2\mu\rho+\alpha_1 r^2 - r\alpha_3 - 2\alpha_1 r\mu + \mu\alpha_3 + \alpha_1\mu + \alpha_2) = (32)\\ &= \Delta+\sigma^2\Psi. \quad (33)\end{aligned}$$

Also, Δ and ρ are as before.

Again, it is useful to look separately at $r=\mu$, and $r>\mu$. Despite the fact that prices are volatile, the uncertainty surrounding prices does not influence the results for $r=\mu$, as the term that incorporates the price volatility is eliminated. It is as if the problem is deterministic when the firm chooses to optimally adopt at $t=\tau$. Therefore, for $r=\mu$ the solution is similar to the corresponding deterministic one. Thus, in this section, we focus on $r>\mu$.

The condition for the firm to decide about adoption at $t=\tau$ is now given by

$$-\frac{a_0\upsilon^2(r-\mu)^2}{4(\Delta+\sigma^2\Psi)}p^2 - \frac{\rho\upsilon}{a_0(1+\upsilon)}S^2 - ca_0 - k = 0, \quad (34)$$

which depends both on the level of the stock, S, and prices, p. Thus, a relationship between S and p is derived, representing the boundary that separates the adoption region from the non-adoption one.

The intercept in the horizontal axis is the same as in the deterministic case, given by (24),while the intercept in the vertical axis is now given by

$$p^+ = \sqrt[2]{\frac{-4(ca_0+k)(\Delta+\sigma^2\Psi)}{a_0\upsilon^2(r-\mu)^2}}. \quad (35)$$

As $\rho<0$, the slope of the boundary separating the adoption region from the non-adoption one depends on the sign of $(\Delta+\sigma^2\Psi)$, which is assumed to be negative in order to have a well-defined problem. Given $(\Delta+\sigma^2\Psi)<0$, we can find pairs (p^{**},S^{**}) for which condition (34) is satisfied, representing the boundary that separates the adoption region from the non-adoption one. As before, it is decreasing at a decreasing rate and it behaves similarly with respect to the technology level a with which the firm operates.

To determine the location of the adoption and the nonadoption region, we differentiate the left-hand side of (34) with respect to both the stock and prices. While the derivative condition for the stock is still given by equation (21), the other for the resource price changes, and it is given by

$$-\frac{1}{2}a_0\upsilon^2\frac{(r-\mu)^2}{\Delta+\sigma^2\Psi}p. \tag{36}$$

By inspection, in the presence of price volatility, it is clear that S^+ does not change. In contrast, p^+ (35) changes its position depending on the sign of $\frac{\partial\Psi}{\partial\sigma^2}$. As $\mu<0$ implies that $\frac{\partial\Psi}{\partial\sigma^2}>0$, then p^+ decreases with σ^2. Consequently, the rotation of the boundary implies that the adoption region is enlarged, while the non-adoption one shrinks, reinforcing the effect of decreasing prices relative to the corresponding deterministic case. If $\mu>0$ and $\frac{\partial\Psi}{\partial\sigma^2}>0$, the same result occurs. However, as $\mu\to r$, $\frac{\partial\Psi}{\partial\sigma^2}<0$, and the price intercept increases, determining an enlargement of the non-adoption region and a reduction of the adoption one. Therefore, the effect of increasing prices is reinforced relative to the corresponding deterministic case. Figure 3 illustrates these results both for $\frac{\partial\Psi}{\partial\sigma^2}>0$ (boundary moving up) and $\frac{\partial\Psi}{\partial\sigma^2}<0$ (boundary moving down).

4 Anticipated technological improvement

In contrast to previous sections, a general model of a competitive nonrenewable resource extracting firm is used to analyze optimal extraction behavior and optimal technology adoption of an incremental type, assuming that the availability of a new technology is anticipated by the firm at the time the firm initiates the extraction program, both in a deterministic and a stochastic context. The solution to this problem is illustrated by solving numerically a dynamic programming problem for a time horizon of three periods, as it is not possible to solve analytically the adoption problem of the firm when it has simultaneously to decide at each time period how much to extract of the resource stock.[14] The

[14] We only use one technological improvement for simplicity. If at each time period a new technology became available, the number of alternative adoption sequences would increase

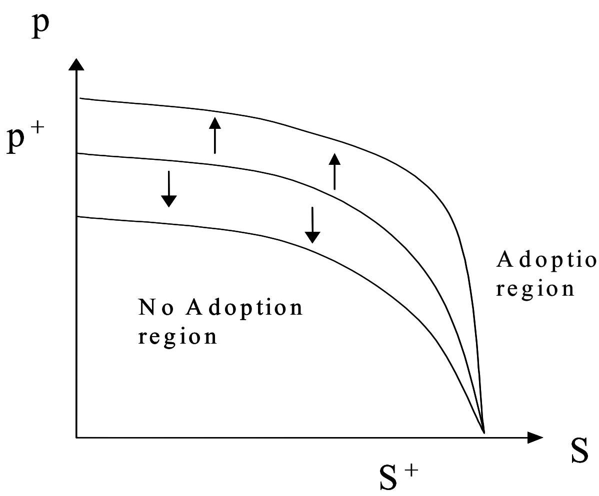

Figure 3: Impact of σ^2 on the boundary

impact of a larger initial stock, higher initial prices and a larger quality upgrade are also examined. Then, the results obtained are compared to those obtained in the unanticipated case. Finally, the case of stochastic prices is examined.

4.1 Deterministic case

In a deterministic context, the firm's problem consists of choosing the extraction path to maximize the present value of profits over time, given the evolution for market prices and the stock, as well as the possibility of adopting a new technology. At any point in time, the firm may either keep using its present technology, or adopt a new one if it is available. Each improvement determines an upgrading in the technological quality.

The problem of the firm can be stated as a finite horizon dynamic programming problem. In order to simplify the problem, we look at a three-period problem and a single new technology, which will become available at $t = 2$, implying that the firm may decide to adopt at $t = 2$ or $T = 3$. The cost of adoption will be incurred only at the time the firm decides to upgrade its technology. Therefore, the firm faces three different scenarios: (i) never adopts the

exponentially.

new technology, (ii) adopts at $t = 2$, implying that it will keep it at $T = 3$, and, finally (iii) waits and only adopts at $T = 3$. The profits associated with each scenario can be calculated, and the scenario with highest profit will be the optimal choice.

In recursive form, the problem for a time horizon of $T = 3$ periods can be stated as follows. In all cases, the stock S_t represents the stock that remains at the beginning of period t. Since the resource is exhausted at the final period, the stock at the beginning of the final period is equal to the amount extracted in that period, and it will be obtained residually. Also, hereafter, NA stands for no adoption, and A for adoption, where the upgrade in technology is given by

$$a' = (1 + v)a.$$

For scenario (i), in which the firm never adopts, the problem consists of choosing the extraction path that maximizes present value of profits given that:

- $t = T = 3:$

$$V_3(S_3, p_3;\ NA) = \underset{e_3}{Max}\{\pi(S_3, p_3; a)\}$$

- $t = 2:$

$$V_2(S_2, p_2, NA; NA) = \underset{e_2}{Max}\{\pi(S_2, p_2; a) + \delta V_3(\cdot)\}$$

$$\begin{aligned} s.t \quad S_3 &= S_2 - e_2 \\ p_3 &= (1 + \mu)p_2 \end{aligned}$$

- $t = 1:$

$$V_1(S_1, p_1, NA; NA, NA) = \underset{e_1}{Max}\{\pi(S_1, p_1; a) + \delta V_2(\cdot)\}$$

$$\begin{aligned} s.t \quad S_2 &= S_1 - e_1 \\ p_2 &= (1 + \mu)p_1 \end{aligned}$$

where the initial stock, S_1, and prices, p_1, are given.

A similar problem can be stated for scenario (ii), where the firm decides to adopt at $t = 2$, switching technology from a to a' at that moment and incurring in an adoption cost of $ca + k$, as well as for scenario (iii), where the firm decides to adopt only at $T = 3$ (see Appendix B). The optimal solution is given by the scenario for which $V_1(.)$ is highest, given the initial conditions on prices and the stock. Thus, once $V_1(.)$ is chosen the optimal pattern of adoption is identified.

4.1.1 Numerical example

The numerical example is solved by applying the procedure described for a three-period horizon, $T = 3$, and is based on a quadratic cost function as before. Moreover, the conditions of the problem are such that the transversality conditions for the stock are satisfied when the resource is exhausted at the final period.[15]

The chosen parameters for the cost function are $\alpha_1 = 4$, $\alpha_2 = 0.1$, and $\alpha_4 = -1.25$. As can be easily checked, for these values of the parameters the cost function is strictly convex. Moreover, we assume that the discount rate is 5%, $r = 0.05$, and the drift term on prices is 2%, $\mu = 0.02$. Also, in the benchmark case, $S(1) = 150$, $p(1) = 33.641$, $c = 5$, $k = 10$, and $a = 10$. Assuming $\upsilon = 0.09$, the upgraded technology quality level is $a' = 10.9$ (see Appendix D, Table 1A).

For the values of the parameters in the benchmark case, the problem of the firm was solved separately for each scenario. The optimal solution corresponds to the scenario that maximizes the value of the firm at $t = 1$, which in this case is scenario (ii), implying that the firm decides to adopt at $t = 2$. As expected, when the firm anticipates the possibility of adopting in the future, it will act strategically by saving resource to the future. Thus, the lowest amount extracted at the initial period is obtained in the optimal scenario. If the firm did not anticipate the chance of adopting in the future, it would choose to extract in the initial period the amount obtained in scenario (i), as the solution of scenario (i) in the first period corresponds to the solution for a firm that does not anticipate the event of any technology adoption. Consequently, it is higher than in the optimal scenario. (see Appendix D, Table 1B).

The results in the benchmark problem were compared to those obtained in different cases: a larger upgrading rate ($\upsilon = 0.3$) (see Appendix D, Table 5), higher initial prices ($p(1) = 43.523$) (see Appendix D, Table 4), and, finally, a change in the stock endowment (a lower and a larger initial stock; see Appendix D, Tables 2 and 3). With a higher initial price and a larger upgrading rate, the optimal scenario is the same as before. As expected, a larger upgrading

[15] The marginal user cost is positive for all periods, see Appendix C.

rate reinforces the importance of technology upgrades on extraction. Thus, the largest decrease in extraction in the initial period occurs in the optimal scenario, and the highest increase in extraction in the final period in scenario (iii). With higher initial prices or a more highly valued resource, the amounts extracted are always larger in the initial period and lower in the final period than in the benchmark case. Therefore, the effect of higher prices on extraction in the initial period reduces the impact of innovation, reducing the incentive to save to the future. Also, the benefits from adoption increase. Comparing now the results obtained when the initial stock changes, we observe that when the resource stock increases to $S(1) = 165$, the optimal scenario is the same, and benefits from adoption increase. In contrast, when the stock is reduced to $S(1) = 65$, the optimal scenario changes, as the firm's optimal decision is to never adopt. However, for $S(1) = 65$, the firm will adopt if prices are high enough, as we show in the next subsection. These results are in line with those previously obtained, according to which (i) larger stocks and higher prices make adoption more profitable for the firm, (ii) large stocks lead to adoption independently of prices, and (iii) low stocks with high enough prices may induce adoption.

4.2 Stochastic case

In this subsection, we assume that there is uncertainty about the evolution of the price of the resource. That is, either prices increase at a rate $0 < \mu < r$ with probability q, or do not change ($\mu = 0$) with probability $(1-q)$. Moreover, the technological improvement becomes available at the initial period, implying that the firm may either decide to adopt immediately or to postpone adoption.[16] Therefore, the problem can be stated as follows:

For scenario (i), in which the firm never adopts, we have for $T = 3$:

- $t = T = 3$:

$$V_3(S_3, p_3;\ NA) = \underset{e_3}{Max}\{\pi(S_3, p_3; a)\}$$

[16] Since there are only three periods, and the decision on extraction in the last period is residual, in order to capture the eventual decision to delay adoption, the technological improvement has to become available already in the initial period, rather than only on the second one, as in the deterministic case.

or,

$$V_3(S_3, p_3';\ NA) = \underset{e_3}{Max}\{\pi(S_3, p_3'; a)\}$$

- $t = 2 :$ [17]

$$V_2(S_2, p_2, q, NA; NA) = \underset{e_2}{Max}\{\pi(S_2, p_2; a) + \delta V_3(S_3, p_3; NA)\} \tag{37}$$

or,

$$V_2(S_2, p_2', q, NA; NA) = \underset{e_2}{Max}\{\pi(S_2, p_2'; a) + \delta V_3(S_3, p_3'; NA)\} \tag{38}$$

- $t = 1 :$

The problem in this period must be solved considering the uncertainty in future prices. Therefore, we have

$$\begin{aligned} V_1(S_1, p_1, q) \quad &= \quad \underset{e_2}{Max}\{\pi(S_1, p_1; a) + \\ &\quad +\delta\left[qV_2(S_2, p_2'; NA, NA) + (1-q)V_2(S_2, p_2; NA, NA)\right]\} \end{aligned}$$

subject to the stock transition, where $p_3' = (1+\mu)p_2'$, $p_2' = (1+\mu)p_1$ for $\mu > 0$, and $p_3 = p_2 = p_1$.

Analogous recursive problems can be written for scenarios (ii) and (iii). In the case of scenario (ii), the problem is similar to the deterministic one, except that the firm adopts in the first period. Thus, for

- $t = 1 :$

$$\begin{aligned} V_1(S_1, p_1, q) \quad &= \quad \underset{e_2}{Max}\{\pi(S_1, p_1; a') - ca - k + \\ &\quad +\delta\left[qV_2(S_2, p_2'; A, A) + (1-q)V_2(S_2, p_2; A, A)\right]\} \end{aligned}$$

subject to the stock transition, where $p_3' = (1+\mu)p_2'$, $p_2' = (1+\mu)p_1$ for $\mu > 0$, and $p_3 = p_2 = p_1$, as before (see Appendix B).

In the case of scenario (iii), there are different alternatives to be considered (see Appendix B), as the decision to adopt may depend upon the realization of uncertainty. The alternative presented below, labeled $V_1^5(S_1, p_1, q)$, is the one that maximizes the initial value when solving for the example. Thus,

[17] We are assuming, for simplicity, that all the uncertainty is solved at $t = 2$.

- $t = 1$:

$$\begin{aligned} V_1^5(S_1, p_1, q) &= \underset{e_2}{Max}\{\pi(S_1, p_1; a) + \\ &\quad +\delta\left[qV_2(S_2, p_2'; A, A) + (1-q)V_2(S_2, p_2; NA, NA)\right]\} \end{aligned}$$

Solving this problem for $S(1) = 65$, $p_1 = p_2 = p_3 = 75$, $p_3' = 99.188$, $p_2' = 86.25$, $p_1 = 75$, for $\mu = 0.15$ and $r = 0.2$, we obtain that the optimal solution is scenario (ii), or to adopt at $t = 1$ if $q > 0.05$, but it is scenario (iii) if $q = 0.03$. That is, with uncertain benefits from adoption the firm prefers to wait and adopt later rather than adopt immediately. The corresponding optimal values for the initial period are: $V_1^* = 4066.4$ in scenario (i), $V_1^* = 4057.7$ in scenario (ii), and $V_1^* = 4072$ in scenario (iii) in the case described. For $q = 0$ the firm decides not to adopt (scenario (i)), while for $q = 1$ decides to adopt at $t = 1$ (scenario (ii)).

5 Conclusions

Empirical research shows that the role played by technology adoption in the natural resource industry is considered to be the determinant factor in extraction cost decrease, responding to the continuing search for lower costs in a competitive market.

In this paper, the optimal extraction and technology adoption decisions are modeled for a competitive nonrenewable resource extracting firm, both in a deterministic and in a stochastic environment, when the firm either anticipates adoption or not. It is assumed that better technology reduces the marginal cost of production but has a known adoption cost. Thus, at the time the new technology is available, adoption will only occur if net benefits are positive. In the unanticipated case a boundary separating the adoption region from the non-adoption one is defined.

In the presence of a resource stock, with a quadratic cost function, we show that the main driving force of adoption is the possibility of taking advantage of lower costs. In fact, for firms with more depleted stock levels, the technological opportunities can only be applied to a smaller amount of the stock, reducing net benefits from adoption. In order for a firm with a low stock level to choose to adopt, prices have to be high enough. Therefore, the price level is also crucial to the adoption/non-adoption decision.

If adoption costs depend on the level of the upgrading rate and the firm does not anticipate the technological improvement, as the marginal benefit of the upgrading rate is positive with respect to both the stock level and prices, firms choosing lower intensity levels are those with more depleted stocks and facing lower prices. Therefore, the level of prices turns out to be crucial not only to the adoption decision, but also to the optimal choice of the intensity of adoption in the presence of a nonrenewable resource. In this context, we may reinterpret some of the results in Pindyck [12] on exploratory effort. When reserves are large and prices are steadily increasing, as the exploratory effort is never enough to compensate for extraction, reserves will be decreasing over time, as in our case. The path for the exploratory effort, increasing first and then decreasing, can be interpreted in terms of our results as the firm choosing higher intensity of adoption when reserves are large, suggesting that benefits from adoption are larger for large stocks, as exploratory effort is more intense when reserves are large.

With price volatility, the adoption decision is also affected by the variance of price. With increasing prices, volatility tends to make adoption less likely, while for decreasing prices the opposite occurs.

Finally, for the case of anticipated technological improvements, the extraction decision of the firm changes for the entire planning horizon, as adoption decisions are incorporated from the start. The problem is solved numerically for a three-period dynamic programming problem, in order to solve simultaneously for the optimal extraction and optimal timing of adoption. As expected, the firm acts strategically, reducing extraction in the initial period, in order to save resource for the future when the possibility of adoption is presented. As in the unanticipated case, the benefits for the firm increase with the stock as well as with prices. Moreover, with sufficiently large stocks the adoption decision does not depend on prices. In contrast, for low stocks, the firm may decide to adopt only when prices are high enough. When benefits from adoption are uncertain, namely by assuming that the evolution of resource prices is uncertain, the firm may decide to wait and adopt only if prices increase rather than adopt immediately.

A Characterization of optimal paths

A.1 For the case $r = \mu$

In this case, $V(.)$ is given by

$$V(p, S; a) = \frac{\rho}{a_0} S^2 + Sp.$$

When $S = 0$, the transversality condition holds

$$V(p, 0; a_0) = 0.$$

Moreover, along the optimal path for extraction, that is, for

$$e^* = -\frac{2\rho + \alpha_4}{2\alpha_1} S,$$

we can show that the marginal extraction cost is driven to zero when $S = 0$. For $S > 0$, the marginal extraction cost is always positive.

As expected, the marginal opportunity cost of the resource is always positive, for $p > 0$, when $S = 0$, as $V_S = p$. For any $S > 0$, the opportunity cost is positive as long as $p > -\frac{2\rho}{a_0} S$; in particular, for the initial stock $p_0 > -\frac{2\rho}{a_0} S_0$.

Therefore, the transversality condition for the stock holds as $\lim_{t\to\infty} V_{S_t} \exp(-rt) = p_0 > 0$, since $r = \mu$, implying that $\lim_{t\to\infty} V_{S_t} \exp(-rt) S_t = 0$ as $\lim_{t\to\infty} S_t \to 0$.

A.2 For the case $r > \mu$

Now the optimal extraction policy for an interior solution is given by

$$e^* = -\frac{2\rho + \alpha_4}{2\alpha_1} S - \frac{a_0(r - \mu)}{2\rho + \alpha_4 - 2\alpha_1(r - \mu)} p$$

As expected, the opportunity cost of the resource is always positive, for $p > 0$, when $S = 0$, as follows:

$$V_S = \frac{2\rho + \alpha_4}{2\rho - 2r\alpha_1 + \alpha_4 + 2\mu\alpha_1} p$$

for values of the parameters that satisfy all the relevant conditions.

For any $S > 0$, the opportunity cost is positive as long as

$$p > \frac{-\frac{2\rho}{a_0}}{\frac{2\rho+\alpha_4}{2\rho-2r\alpha_1+\alpha_4+2\mu\alpha_1}} S$$

and, in particular, for S_0,

$$p_0 > \frac{-\frac{2\rho}{a_0}}{\frac{2\rho+\alpha_4}{2\rho-2r\alpha_1+\alpha_4+2\mu\alpha_1}} S_0,$$

which is always satisfied for values of the parameters that verify all the relevant conditions.

Therefore, the transversality condition for the stock is $\lim_{t\to\infty} V_{S_t} \exp(-rt) S_t = 0$. As $V_{S_t} \exp(-rt)$ approaches zero at a rate $r - \mu$, if the stock approaches zero at least at the same rate the transversality condition is satisfied.

A.3 Volatile prices: case $r > \mu$

The optimal extraction policy for an interior solution is given by

$$e^* = -\frac{2\rho + \alpha_4}{2\alpha_1} S - \frac{a_0(r-\mu)}{2\rho + \alpha_4 - 2\alpha_1(r-\mu)} p$$

As expected, the opportunity cost of the resource is always positive, for $p > 0$, when $S = 0$, as follows

$$V_S = \frac{2\rho + \alpha_4}{2\rho - 2r\alpha_1 + \alpha_4 + 2\mu\alpha_1} p$$

for values of the parameters that satisfy all the relevant conditions.

For any $S > 0$, the opportunity cost is positive as long as

$$p > \frac{-\frac{2\rho}{a_0}}{\frac{2\rho+\alpha_4}{2\rho-2r\alpha_1+\alpha_4+2\mu\alpha_1}} S$$

and, in particular, for S_0,

$$p_0 > \frac{-\frac{2\rho}{a_0}}{\frac{2\rho+\alpha_4}{2\rho-2r\alpha_1+\alpha_4+2\mu\alpha_1}} S_0,$$

which is always satisfied for values of the parameters that verify all the relevant conditions. As before, the transversality condition for the stock holds in the above conditions.

B.1 Deterministic case

For scenario (ii), the firm adopts at $t = 2$ so we have:

- $t = T = 3 : V_3(S_3, p_3;\ A) = \underset{e_3}{Max}\{\pi(S_3, p_3; a')\}$

  where $a' = a(1 + \upsilon)$.

- $t = 2 : V_2(S_2, p_2, A; A) = \underset{e_2}{Max}\{\pi(S_2, p_2; a') - ca - k + \delta V_3(\cdot)\}$

  subject to the transitions for the stock and prices, as before.

- $t = 1 : V_1(S_1, p_1, NA; A, A) = \underset{e_1}{Max}\{\pi(S_1, p_1; a) + \delta V_2(\cdot)\}$

  where the initial stock, S_1, and prices, p_1, are given, and the transition equations are taken into account.

Finally, for scenario (iii), where the firm decides to adopt only at $T = 3$, the problem consists of:

- $t = T = 3 : V_3(S_3, p_3;\ A) = \underset{e_3}{Max}\{\pi(S_3, p_3; a') - ca - k\}$
- $t = 2 : V_2(S_2, p_2, NA; A) = \underset{e_2}{Max}\{\pi(S_2, p_2; a) + \delta V_3(\cdot)\}$

  subject to the transitions for stock and prices.

- $t = 1 : V_1(S_1, p_1, NA; NA, A) = \underset{e_1}{Max}\{\pi(S_1, p_1; a) + \delta V_2(\cdot)\}$

  again subject to the transitions for stock and prices, given S_1 and p_1.

B.2 Stochastic case

For scenario (ii), where the firm decides to adopt at $t = 1$:

- $t = T = 3 : V_3(S_3, p_3;\ A) = \underset{e_3}{Max}\{\pi(S_3, p_3; a')\}$ or $V_3(S_3, p_3';\ A) = \underset{e_3}{Max}\{\pi(S_3, p_3'; a')\}$.
- $t = 2 : V_2(S_2, p_2, A; A) = \underset{e_2}{Max}\{\pi(S_2, p_2; a') + \delta V_3(S_3, p_3; A)\}$ or $V_2(S_2, p_2', A; A) = \underset{e_2}{Max}\{\pi(S_2, p_2'; a') + \delta V_3(S_3, p_3'; A)\}$.

- $t = 1:$

$$V_1(S_1, p_1; q) = \underset{e_1}{Max}\{\pi(S_1, p_1; a') - ca - k + \\ +\delta\left[qV_2(S_2, p_2'; A, A) + (1-q)V_2(S_2, p_2; A, A)\right]\}$$

where the initial stock, S_1, and prices, p_1, are given, satisfying the two transitions, respectively.

Finally, for scenario (iii), where the firm decides to adopt at $t = 2$ or $T = 3$, the problem consists of:

- $t = T = 3: V_3(S_3, p_3;\ A) = \underset{e_3}{Max}\{\pi(S_3, p_3; a') - ca - k\}$ or

$V_3(S_3, p_3';\ A) = \underset{e_3}{Max}\{\pi(S_3, p_3'; a') - ca - k\}$ or
$V_3(S_3, p_3;\ A) = \underset{e_3}{Max}\{\pi(S_3, p_3; a')\}$ or
$V_3(S_3, p_3';\ A) = \underset{e_3}{Max}\{\pi(S_3, p_3'; a')\}$.

- $t = 2:$

$$V_2(S_2, p_2', A; A) = \underset{e_2}{Max}\{\pi(S_2, p_2'; a') - ca - k + \delta V_3(S_3, p_3'; A),$$

or

$$V_2(S_2, p_2, A; A) = \underset{e_2}{Max}\{\pi(S_2, p_2; a') - ca - k + \delta V_3(S_3, p_3;\ A)\}$$

or

$$V_2(S_2, p_2', NA; A) = \underset{e_2}{Max}\{\pi(S_2, p_2'; a) + \delta V_3(S_3, p_3'; A),$$

and

$$V_2(S_2, p_2, NA; A) = \underset{e_2}{Max}\{\pi(S_2, p_2; a) + \delta V_3(S_3, p_3; A),$$

subject to the transitions for the stock and prices. The alternative of not adopting both in $t = 2$ and $T = 3$ was already derived in scenario (i).

- $t = 1:$

$$V_1^1(S_1, p_1; q) = \underset{e_1}{Max}\{\pi(S_1, p_1; a) + \\ +\delta\left[qV_2(S_2, p_2', q; A, A) + (1-p)V_2(S_2, p_2, q; A, A)\right]\}$$

or

$$V_1^2(S_1, p_1; q) = \underset{e_1}{Max}\{\pi(S_1, p_1; a) + \\ +\delta\left[qV_2(S_2, p_2', q; NA, A) + (1-p)V_2(S_2, p_2, q; A, A)\right]\}$$

or

$$V_1^3(S_1, p_1; q) = \underset{e_1}{Max}\{\pi(S_1, p_1; a) + \\ +\delta\left[qV_2(S_2, p_2', q; NA, NA) + (1-p)V_2(S_2, p_2, q; A, A)\right]\}$$

or

$$V_1^4(S_1, p_1; q) = \underset{e_1}{Max}\{\pi(S_1, p_1; a) + \\ +\delta\left[qV_2(S_2, p_2', q; A, A) + (1-p)V_2(S_2, p_2, q; NA, A)\right]\}$$

or

$$V_1^5(S_1, p_1; q) = \underset{e_1}{Max}\{\pi(S_1, p_1; a) + \\ +\delta\left[qV_2(S_2, p_2', q; A, A) + (1-p)V_2(S_2, p_2, q; NA, NA)\right]\}$$

subject to the transitions for the stock and prices, given S_1 and p_1. The other alternative of never adopting was already obtained in scenario (i).

C Marginal user cost of the resource in the anticipated problem

The marginal user cost at each time period can be derived by using the Envelope Theorem at each time period. Thus, at $T = 3$, we obtain:

$$\frac{\partial V_3}{\partial S_3} = -\frac{1}{a}(2\alpha_2 S_3 + \alpha_4 e_3)$$

or,

$$\frac{\partial V_3}{\partial S_3} = -\frac{1}{a}e_3(2\alpha_2 + \alpha_4).$$

since is evaluated at the optimum. Therefore, the marginal user cost $\frac{\partial V_3}{\partial S_3} > 0$ as long as $\frac{-\alpha_4}{2\alpha_2} > 1$, which is satisfied for the values of the parameters of the cost function.

At $t = 2$, the marginal user cost is given by

$$\frac{\partial V_2}{\partial S_2} = -\frac{1}{a}(2\alpha_2 S_2 + \alpha_4 e_2) + \delta \frac{\partial V_3}{\partial S_3}.$$

Given that $\frac{\partial V_3}{\partial S_3} > 0$, then a sufficient condition for $\frac{\partial V_2}{\partial S_2} > 0$ is that $\frac{-\alpha_4}{2\alpha_2} > \frac{S_2}{e_2}$, which always hold as well.

Finally, by following a similar procedure, a sufficient condition for the marginal user cost in period $t = 1$, $\frac{\partial V_1}{\partial S_1}$, to be positive is that $\frac{-\alpha_4}{2\alpha_2} > \frac{S_1}{e_1}$, which also holds.

In summary, the sufficient conditions for exhaustion in the above problem are that $\frac{-\alpha_4}{2\alpha_2} > \frac{S_t}{e_t}$, for $t = 1, 2, 3$.

Based on a similar argument, one can show that the same holds in the stochastic case.

D Tables for the numerical example

Table 1A

	Benchmark Case
$S(1)$	150
p_1	33.641
μ	0.02
r	0.05
a	10
v	0.09
a'	10.9
c	5
k	10

Table 1B

Solution (Benchmark Case)	scenario (i)	scenario (ii)	scenario (iii)
e_1^*	52.38	50.338	51.22
e_2^*	49.28	50.362	48.168
e_3^*	48.34	49.3	50.612
V_1^*	3519.64	**3551.04**	3517.62
V_2^*	2202.6	2259.9	2214.0
V_3^*	1025.9	1090	1041.7

Table 2

Solution $S(1) = 65$	scenario (i)	scenario (ii)	scenario (iii)
e_1^*	23.046	22.262	23.109
e_2^*	21.596	21.872	20.862
e_3^*	20.358	20.506	21.029
V_1^*	**1866.2**	1825.1	1820.9

Table 3

Solution $S(1) = 165$	scenario (i)	scenario (ii)	scenario (iii)
e_1^*	57.557	55.228	56.181
e_2^*	54.166	55.39	52.987
e_3^*	53.277	54.382	55.832
V_1^*	2117.64	**3769.29**	3728.35

Table 4

Solution $p_1 = 43.253$	scenario (i)	scenario (ii)	scenario (iii)
e_1^*	52.555	50.746	51.682
e_2^*	49.402	50.386	48.162
e_3^*	48.043	48.868	50.156
V_1^*	4921.7	**4952.4**	4918.8

Table 5

Solution $a' = 13$	scenario (i)	scenario (ii)	scenario (iii)
e_1^*	52.38	46.988	49.055
e_2^*	49.28	52.181	45.789
e_3^*	48.34	50.831	55.156
V_1^*	3519.64	**3718.3**	3625.0

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