Uncertain resources, substitutes, and a theory of mutual dependence

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Abstract

We consider a model of resource dependence where only the seller knows the resource reserve. The model captures phenomena such as trust in the relationship and "bribing" for continuation through generous supplies. It also explains supply shocks in equilibrium: privately informed sellers have incentives to reveal their types too late through a supply disruption after which their exploit the consumers inability to immediately adjust demand. Two puzzles that a standard exhaustible-resource theory cannot explain are resolved: sellers have an incentive to overstate their resources rather than emphasize scarcity, and buyer's can switch to alternatives before exhausting the resource thereby leaving socially valuable resource in the ground.

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1 Introduction

At the turn of the 20th century, agricultural nitrogen became a key scarce natural resource commodity in Europe, leading Sir William Crookes, the president of the British Association for the Advancement of Science, in 1889 to appeal to chemists to develop a synthetic solution to the nitrogen problem, as otherwise "All England and all civilized nations stand in deadly peril of not having enough to eat", potentially as early as in the 1930's. The early industrialized nations had become critically dependent on the deposits of natural sodium nitrogen from the Atacama desert of Chile.[1] Chile was the sole supplier of this commodity in four decades until 1920's. Then, the resource monopoly died out when the importing countries transited towards a synthetic substitute derived through the Haber-Bosch process, named after the two Nobel Prize winners who developed the process that turned out be "one of the most important inventions in the chemical industry ever." (Mokyr, 1998).[2,3] After the innovation, it took more than a decade for the world consumption to depart from the natural supplies. Surprisingly, the monopoly did not only face a competitor but lost its business entirely: a significant fraction of the resource was left unused (Smil, 2001). The resource was relatively easy to extract (Whitbeck, 1931), and, in view of the standard exhaustible-resource theory, it is surprising that a homogenous substitute made the resource obsolete (Dasgupta and Heal, 1979). Given that the valuable resource was left unused, it seems that the adoption of the substitute technology was too much hurried.

Coming to the present-day resource relationships, another puzzle emerges. The following headline from the Telegraph of March 22, 2013 is revealing:[4]

> "The world's oil reserves have been exaggerated by up to a third"

Or from The Huffington Post September 2, 2011:

> "Wikileaks Cable: Saudi Oil Reserves Exaggerated By 40 Percent"

[1]For the fascinating history of nitrogen use, natural fixation and synthetic production, see, e.g., Leigh (2004) and Smil (2001).

[2]Whitbeck (1931) provides a succinct description of the resource reserve, its exploitation technology, costs, production numbers, as well as the basic facts of the substitute entry.

[3]See Montéon (1975) for the role of British capital in the resource exploitation, and, e.g., Brown (1963) for the Chilean government's resource-use policies.

[4]These headlines are obtained through a simple Google search. A more systematic coverage of the concerns regarding the size of the Saudi reserves is in Simmons (2005).

Why would resource sellers exaggerate their reserves? Prices increase with the perceived scarcity; if anything, the standard resource theory suggests that dominant resource sellers should underestimate rather than overestimate their resource holdings (Hotelling, 1931). In contrast, the dominant resource sellers often communicate with the market to emphasize stability and the security of supply.[5]

The examples seem to capture the concern that when planning for the use of resources and thus future dependence on them, it is essential to take account of the fact that we do not know how long resources will precisely last. Yet few discussions of exhaustible resource allocations over time give this problem due consideration. Pindyck (1980) (and others following) are aware of the uncertainty of future resource reserves. They analyze uncertain discovery rates, through which shocks temporarily affect supplies and demand. For one reason or another, they did not expound on resource uncertainties arising from asymmetric information, and on how such uncertainties can lead to drastic changes in behavior. Resource theorists seem to have disregarded the problem altogether. Clearly, the standard resource use models fail to capture the essence of the buyer-seller relationships illustrate above — that is, private information and reasons for caution on the consumer side that may explain hurried transitions away from resources, as well as the "demand management" motives of the seller side. We intend to go to the other extreme, by concentrating entirely on uncertainties arising from privately informed resource owners and ignoring the other uncertainties which a resource market must normally cope with.

In this paper, we develop a simple model of resource dependence to capture exactly these features. The buyer side faces adjustment delays in developing and adopting the alternative supply sources: the dependence on the resource must continue for some time even if the decision to stop is made today. Only the seller side knows the exact size of the resource stock but cannot credibly communicate it because all seller types benefit from reporting large stocks. The consumer side must thus decide how long to continue dependence on this uncertain resource; beliefs regarding the remaining resource can be updated based on the history of market behavior. The setting captures also the sellers' motive to keep trust in the relationship: "The security of supply" is communicated by prices and thus supplies that signal resource levels that a critically small resource owner would not find rational to offer.

[5]To illustrate: "We've got almost 30 percent of the world's oil. For us, the objective is to assure that oil remains an economically competitive source of energy. Oil prices that are too high reduce demand growth for oil and encourage the development of alternative energy sources" (Adel al-Jubeir, foreign policy adviser of crown prince Abdullah of Saudi Arabia, Herald Tribune, Jan 24, 2007).

The model produces a number of results that challenge the standard resource models and that can provide useful insights to the past and present resource dependence challenges.

First, we describe a supply shock as an equilibrium phenomenon: privately informed sellers have incentives to reveal their types too late, generating supply shocks after which their exploit the buyers inability to move to substitutes immediately. The buyer side thus rationally accepts the chance of being exploited but requires a compensation, through generous supplies prior to the shock, for accepting this risk. We believe this equilibrium prediction provides a perspective on "oil dependence".

Second, we show that the resource supplies increase with the pessimism regarding the consumer side estimate of the reserve. Thus, the smaller is the expected resource stock, the larger is the required supply that keeps the consumer in the relationship. This implication for supplies is perfectly orthogonal to the the standard resource theory where a greater scarcity always lowers supplies. Alternatively stated, the result implies that larger supplies make the consumer side to accept a larger potential supply disruption and still continue the relationship.

Finally, we analyze how the determinants of the dependence shape the equilibrium relationship. A sufficiently good outside option can lead the buyers to move away from the resource even though, in expectations, some resource will be left in the ground. This is one manifestation of the social cost arising from the inability measure precisely the cost of continuation of the resource consumption; such an outcome would never occur if the resource reserve were public knowledge. The same outcome arises when adjustment delays in moving to the alternatives are long enough; in such cases, the consumer side adopts the alternative as soon as possible, and the seller is unable to "bribe" postponement through supply policies.

The resource-dependence problem under asymmetric information has not been considered before. We have two strategic parties but the bargaining is not explicit as the resource is traded in the market rather than in a direct bilateral relationship.[6] The timing assumptions seek to support a market interpretation and capture the implicit nature of bargaining. Here we follow Gerlagh and Liski (2011) who do not consider hidden information; the substance matter of the current paper follows from informational

[6] Following Joskow (1987), one should ask why such bilateral contracts do not emerge, despite the resource specific infrastructure on the consumer side? We conjecture that the answer is related to the fact that the parties are more elusive that in firm-level contracting, and that the asset specificity develops gradually.

asymmetries.[7] While not cheap talk (Crawford and Sobel, 1982), there is an element of it in the periodic interaction: the seller offers supplies to influence beliefs and, then, if the buyer continues without investing, the offer is implicitly accepted and the supply offer is actually delivered; if the offer is "declined" and investment takes place, then the seller does not have to deliver the supply offer. These assumptions preserve a non-trivial sharing of the surplus, depending on the primitives such as adjustment delays, stock size, and cost of the outside option.

The setting shares similarities with the literature on the Coase conjecture — Hörner and Kamien (2004) establish that the resource monopsony problem is equivalent to the durable-good monopoly problem.[8] However, our setting is a bilateral monopoly with dynamic signaling (Fudenberg and Tirole, 1983) with a different strategic variable (stopping decision with delay), leading to quite different equilibrium outcomes. In particular, the informed agent takes initiative in the relationship; after all, it is the seller who interacts with the consumers, and the buyer's agent (government) responds to the information generated by that market interaction.[9]

We describe a stationary equilibrium in a situation where the informed agent (seller) takes initiative by offering supplies to the market, and the uninformed agent decides whether to continue the relationship. While this timing takes us to the domain of dynamic signaling, and thus leads to multiplicity of sequential equilibria (Fudenberg and Tirole 1983; see also Ausubel et al., 2002), the structure of stationary equilibria is relatively simple due to the nature of the buyer's stopping problem. In fact, we make assumptions

[7] To be explicit, the two puzzles presented — the consumer side caution and the seller side over-reporting of reserves — cannot be addressed without hidden information.

[8] There is a long tradition in resource economics to study the strategic interactions in the resource markets, although the formal connection to the durable-good theory was first presented by Hörner and Kamien (2004). There are two branches of literature that are Coasian in spirit: the optimal tariff literature (e.g., Newbery, 1983; Maskin and Newbery,1990; see Karp and Newbery 1993 for a review); and the literature on strategic R&D and technology adoption in exhaustible-resource markets (Dasgupta et al., 1983; Gallini et al., 1983, and Hoel, 1983; Lewis et al.,1986; Harris and Vickers 1995). The common theme in this literature is that the co-ordinated action on the buyer side can be used to decrease the seller's resource rent. None of these papers consider asymmetric information.

[9] In a typical durable-good problem, the uninformed agent makes repeated offers to the informed agent whose valuation is private information (see, e.g., Gul et al. 1986). Assuming screening of the seller by the uninformed buyer would be at odds with the market interaction. This interpretation would be difficult to achieve under a structure where the uninformed agent takes initiative in screening the informed agent. Deneckere and Liang (2006) consider screening, which is more natural in their case since there is no market involved.

that ensure existence of stationarity not only in terms of beliefs but also as regards to the resource stock: under continuation, the buyer updates beliefs of the seller's size upwards at the same rate as the resource stock is exhausted. This allows a relatively simple analysis while keeping the substance-related key concepts in the analysis, such as the resource scarcity, substitute surplus, and the determinants of the resource dependence. Clearly, we cannot make claims regarding generality, but we will discuss extensions that we have elaborated in the working paper version.

The paper is organized as follows. In the next Section, we introduce the basic notation, assumptions, and explain the beliefs and restrictions on which we build the equilibrium analysis. Both the buyer and the seller face a dynamic problem but the setting preserves the nature of the strategic interaction even without discounting, allowing us to considerably simplify the dynamic analysis. We will argue that discounting does not fundamentally alter the findings. Section 3 characterizes the equilibrium and the main results. Section 4 discusses extensions; to address some fundamental concerns regarding the stationary equilibrium, we develop a non-stationary version of the model in the supplementary material. Section 5 concludes.

2 The Model

2.1 Basic setting

There are two strategic agents: the seller of an exhaustible resource and the buyer. In each period t, the buyer has a downward sloping demand for the resource consumption, and the seller has full powers to set the price of that consumption. Thus, by setting the price, the seller can control how much is consumed in each period: given price p_t, the buyer consumes all units with valuation higher than p_t, defining quantity q_t consumed at t.

However, in the same period after observing p_t, the buyer can decide to initiate the ending of the relationship. The buyer's and seller's interaction is about whether the buyer adopts the substitute or not, i.e., chooses $d_t \in \{0, 1\}$. Setting p_t and choosing d_t are the only strategic choices. The buyer's problem is that only the seller knows the exact size of the initial stock, s_0, and thus how much is left after some cumulative use, Q_t.

Strategic interactions take place at discrete time points in the time line, $t_i = \varepsilon i$ where $i = 1, 2, 3, ...$ The choices at each t_i freeze actions for the next ε interval of time. Below, we let ε converge to zero to analyze the continuous-time limit. After the coming ε units of time, the interaction starts anew. At given t, the buyer has beliefs on the seller's remaining resource stock. The timing of moves is:

1. The seller offers supply at price p_t;
2. The buyer updates beliefs and decides on investment $d_t \in \{0, 1\}$;
3. If the buyer does not invest, $d_t = 0$, markets clear at p_t; q_t is consumed for $[t, t + \varepsilon]$ and the game continues. If the buyer invests, $d_t = 1$, the strategic interaction stops.

We make these timing assumptions to create a bargaining situation that sustains a division of surplus that depends on the fundamentals of the problem, even when time discounting is absent. Since the buyer can respond to p_t in the same period, the seller will have to choose a price that gives the buyer at least the surplus achievable from stopping immediately.

We consider thus a strategic cake-eating problem where only the seller knows the exact size of the cake. The buyer cares about the size of the remaining cake because the buyer cannot immediately move to consume alternative supplies. After choosing $d_t = 1$, the buyer still needs to consume the resource for $k > 0$ units of time. Here, k is the time-to-build for the substitute, capturing the ease with which demand can be changed. That is, k measures the degree of resource dependence. Once in place, the substitute replaces the resource irreversibly. By this assumption, the seller has no future after the time-to-build period. By choosing $d_t = 1$ the buyer forces the seller to sell the remaining resource stock during the time window of length k; if there is too much of the stock left, some of it may be left unused. On the other hand, conditional on $d_t = 1$, the seller has no other concerns than his remaining profits during the time the seller is still using the resource; arriving this stage with little stock allows the seller to exploit the buyer dependence and reap high prices. Figure 1 illustrates the timeline.

The buyer's utility flow from consumption q_t is $U(q_t)$, assumed to be bounded, differentiable, and strictly concave. If there is no alternative supply source in place (holds by assumption for at least for the first k units of time), the buyer can only consume from the seller's resource. The seller's profit flow is $\pi(p_t) = p_t q_t(p_t)$ where $q_t(p_t)$ is the demand function that satisfies $p_t = U'(q_t(p_t))$. For the analysis, it is convenient to work with quantities, and we write $\pi(q_t) = p(q_t)q_t$ with the inverse demand $p(q_t) = U'(q_t)$ when the resource is supplied to the market at rate q_t. The seller offers the resource at price p_t, but as utility and demand are public knowledge and we consider a monopolist, we can also restate the equilibrium as one where the seller offers a quantity q_t. The buyer's net surplus flow $u(q_t) = U(q_t) - p(q_t)q_t$ is the consumer surplus. We assume that both u and π are strictly concave in quantities, but we will relax this assumption on u later. When the substitute is in place, it can be produced at constant price $\bar{p}$, yielding a surplus flow of size $\bar{u} = U(\bar{q}) - \bar{p}\bar{q}$, where $\bar{p} = U'(\bar{q})$.[10] There will be no discounting in the analysis.

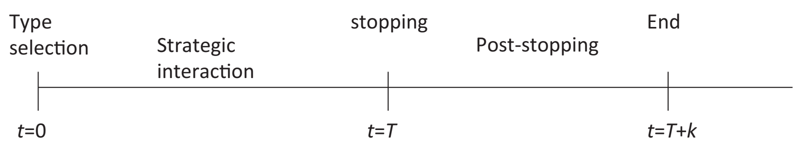

Figure 1: Timeline

2.2 Equilibrium conjecture

We are interested in stationary equilibria where the buyer's strategy will be of the cut-off type: the buyer will stop if the offered price is above a given threshold. Also, the seller types that are above a cut-off stock size find it optimal to offer a continuation price; others will trigger stopping.

To this end, we consider exponential prior distribution for seller types, $s_0 \sim$Exp(α), with parameter $\alpha > 0$. Considering consumption q_t at time t, beliefs change because the support of the initial stock drifts down at this rate. However, in the continuation of the game, the buyer continuously learns that the seller is not of the smallest type. In a stationary equilibrium, the drift in beliefs upwards exactly equals the rate at which the physical stock declines so that the equilibrium beliefs remain stationary and are fully

[10]The source of the long-run surplus flow is not material for the results; it need not be linked to the original utility formulation. For some interpretations, it is useful to separate the cost of substitute supply $\bar{p}$ from adjustment delay k.

determined by two parameters: s^L for the smallest possible type willing to continue, and the hazard rate α for the distribution $(s_t - s^L) \sim$Exp(α) where s_t denotes the possible values for the reserve at t. Such beliefs will then be represented through a density function $f(s)$, and the corresponding probability that the resource stock falls short of s is given by the cumulative distribution

$$F(s) = \begin{cases} 1 - e^{-\alpha(s-s^L)} \text{ if } s > s^L \\ 0 \text{ otherwise.} \end{cases}$$

Notice that while the hazard rate α is a constant, determined by the initial distribution at time $t = 0$, the lower bound s^L is an endogenous characteristic of the equilibrium. Both a lower value for s^L, and a higher value for α represent more pessimistic beliefs about the resource stock, as $\mathbb{E}[s] = s^L + 1/\alpha$. A larger value for α represents both a more pessimistic view, but also a lower degree of asymmetry, as $\text{Var}[s] = 1/\alpha^2$.

To support such stationary beliefs in equilibrium, the buyer must thus continuously learn that the seller is not of the smallest type. Considering a short interval of time, denoted ε, with supply rate q and the initial belief s^L for the lowest type, we will verify that the buyer infers from the equilibrium conditions that if the seller supplies the equilibrium resource supply, denoted q^I, then the seller's type is not in $(s^L, s^L + \varepsilon q^I]$. That is, in the continuation of the game, the Bayesian updating supports stationary current beliefs that are independent of cumulative supplies Q_t.

We thus look for a stationary strategy for the seller which is a function that maps from the remaining stock to a supply, given the publicly known belief, $q_t = \eta(s_t, s^L) \geq 0$.[11] The buyer's strategy is then, given the belief s^L, a function $d_t = \mu(q_t, s^L) \in \{0, 1\}$, i.e., a function that maps the possible supply levels to a decision to continue or stop. The buyer's strategy depends on a cutoff q^I so that $d_t = \mu(q_t, s^L) = 1$ iff $q_t < q^I(s^L)$: the buyer will invest, in equilibrium, if the seller's offer falls short of the required supply q^I.[12] Sellers never supply above the threshold level q^I. As long as the game is in a stationary continuation stage, the (privately observed) resource dynamics satisfy

$$ds_t = -q^I \varepsilon = \eta(s_t, s^L)\varepsilon.$$

The equation simply states that all continuing seller types s_t supply q^I when the buyer's belief is s^L. After the buyer observes q^I, beliefs dynamics in equilibrium are stationary,

[11] Beliefs depend on α too, but we drop it as an arguments, except later when we analyze the effect of α on the equilibrium.

[12] This implies no loss of generality, given our focus on stationary equilibria.

and thus updated beliefs $s^{L'}$ must satisfy

$$s^L + \varepsilon q^I = s^{L'} = \min\{s_t | \eta(s_t, s^L) = q^I\}.$$

The second equation says the separating type is the lowest type that is willing to continue supplying q^I. The game moves to the stopping stage when $\eta(s_t, s^L) < q^I$. For arbitrary short periods ε, we find as the equilibrium condition determining s^L:

$$\begin{aligned} \eta(s_t, s^L) &< q^I(s^L) \text{ if } s_t < s^L \\ \eta(s_t, s^L) &= q^I(s^L) \text{ if } s_t \geq s^L. \end{aligned}$$

When the seller supplies more than required (off-the-equilibrium), we assume passive conjectures: beliefs remain as in equilibrium. This shapes the seller's strategy; in equilibrium, as we will see, no seller supplies more than q^I. The constant beliefs and threshold policy q^I implies that sellers foresee the full continuation path and at each point in time can decide whether it is profitable to offer $q_t \geq q^I$, or not. We find the equilibrium by describing the buyer's strategy $q^I(s^L)$, and the seller's strategy $\eta(s_t, s^L)$.

2.3 Buyer's decision

We describe now how the consumer evaluates the payoff from continuation and stopping the relationship, given the belief on the resource stock. The seller's full strategy will be described in the next section; however, to determine the buyer's strategy, we must first consider the seller's optimal supply after stopping.

Supply after stopping: We call the period after the buyer's investment the *stopping stage* of the resource dependence game. Recall that we assume no discounting, and that the monopolist's marginal profit at any t is derived from the consumer's willingness to pay, which is determined by a strictly concave function $U(q_t)$ before the substitute arrives. Therefore, if the stopping stage begins at t, the seller's optimal supply flow during $\tau \in [t, t+k]$ is

$$q_\tau = \min\{s_t/k, q^m\} \tag{1}$$

where $q^m = \text{argmax}\pi(q)$ is the monopoly supply in the absence of resource stock constraints. To understand this policy, note that since the consumer has the same willingness to pay at each time point, the monopoly allocates scarcity evenly in the time interval $[t, t+k]$ by supplying s_t/k. There is no scarcity if $s_t/k \geqslant q^m$, and then the seller just leaves quantity $s_t - q^m k$ of the resource in the ground.

Stopping payoff: By stopping at t, the buyer ends the game and forces the seller to the supply its remaining resource in $[t, t+k]$; after this time interval, the demand for the resource dies out. But, since the seller's stock is private information, the buyer does not exactly know the supply that follows the decision. Understanding the seller's policy in (1) triggered by stopping, the buyer can evaluate its post-stopping utility flow as $\hat{u}(s/k) = u(\min\{s/k, q^m\})$, conditional on s, in $[t, t+k]$. If the buyer stops at t with beliefs (s^L, α), the total expected strong long-run average surplus (see Dutta, 1991) is:

$$\mathbb{E}_t W^I = \int_{s_t^L}^{\infty} k[\hat{u}(s/k) - \overline{u}] f(s) ds. \tag{2}$$

Expression (2) gives the sum of the instantaneous surpluses in excess of the long-run surplus flow that is obtained after the substitute arrival; expression $\mathbb{E}W^I$ is the appropriate measure of the total consumer surplus in the absence of discounting (see Dutta, 1991; and Gerlagh and Liski, 2011).[13] Intuitively, it measures how much surplus the resource can generate above the outside option.[14]

Continuation payoff: We denote by $\mathbb{E}_t W_t$ the expected payoff under continuation at time t. The consumer evaluates the payoff from stopping the relationship, and compares this to the value of continuation. The equilibrium can only be in the continuation stage if continuation paysoff are at least the same as stopping $\mathbb{E}_t W_t \geq \mathbb{E}_t W_t^I$. If the consumer continues the resource relationship, and receives a supply q_t over a short period ε, the total payoff from time t onwards equals the surplus generated over the interval $[t, t+\varepsilon]$, plus the payoff after that period. There is the probability εh with $h = qf(s^L) = \alpha q$, the hazard rate for the event that at time $t + \varepsilon$ the buyer will have learned that the seller is of a small type $s_t \in (s^L, s^L + \varepsilon q]$, in which case the future payoff becomes $k[\hat{u}(s^L/k) - \overline{u}]$. In the complement event, the buyer continues with the same expected payoff as currently $\mathbb{E}_t W_t$. The expected surplus under continuation is thus:

$$\mathbb{E}_t W_t = \varepsilon[u(q_t) - \overline{u}] + \varepsilon h k[\hat{u}(s^L/k) - \overline{u}] + (1 - \varepsilon h)\mathbb{E}_t W_t. \tag{3}$$

Note that the last two terms have a measure of the costs of delay. The drop in the payoff when the seller turns out to be small, $\mathbb{E}_t W_t^I - k[\hat{u}(s^L/k) - \overline{u}]$, is multiplied by the probability of such an event, εh. In the appendix, we show that this measure for the costs of delay equals the decrease in the expected surplus from consuming at rate q_t:

$$\varepsilon h(\mathbb{E}_t W_t^I - k[\hat{u}(s^L/k) - \overline{u}]) = \varepsilon q \mathbb{E}_t[\hat{u}'(s_t/k)] \tag{4}$$

[13] In the Appendix, we derive this measure as a limit of a discounted surplus measure.

[14] Through k the expression for $\mathbb{E}W^I$ captures the buyer's dependence on the seller. Expression (2) suggests that for short k, $\mathbb{E}W^I$ can actually be increasing in k. However, as we will show, in equilibrium the buyer suffers from a longer k.

We assume (and will verify such is rational) that the seller leaves no surplus to the buyer in excess to the surplus that the buyer receives if investing, thus $\mathbb{E}_t W_t \leq \mathbb{E}_t W_t^I$. Combining the assumption with the continuation condition $\mathbb{E}_t W_t \geq \mathbb{E}_t W_t^I$, we obtain $\mathbb{E}_t W_t = \mathbb{E}_t W_t^I$, and the indifference condition becomes

$$\begin{aligned} \mathbb{E}_t W_t^I &= \varepsilon[u(q_t) - \overline{u}] + \mathbb{E}_t W_t^I - \varepsilon q \mathbb{E}_t[\hat{u}'(s_t/k)] \Rightarrow & (5) \\ u(q_t) &= \overline{u} + q_t \mathbb{E}_t[\hat{u}'(s_t/k)]. & (6) \end{aligned}$$

Indifference between continuation and stopping: We have an indifference condition that keeps the buyer exactly indifferent between stopping now, and delaying stopping by infinitely short time, given current beliefs. We denote the supply that keeps the buyer indifferent by q^I:

$$\begin{aligned} u(q^I) &= \overline{u} + \lambda q^I. & (7) \\ \lambda &= \mathbb{E}\hat{u}'(s/k), & (8) \end{aligned}$$

where we drop time subscripts to emphasize that the core indifference in this paper does not depend on history.

See also Fig. 2. The relation defines the scarcity costs and resource demand that keeps the buyer indifferent as dependent on beliefs: $\lambda(s^L, \alpha)$, and $q^I(s^L, \alpha)$. Supply today, keeping the consumer just indifferent at continuation without calling the substitute into play, should thus provide surplus $u(q)$ that is enough to cover (i) the substitute surplus, $\overline{u}$, that is lost irreversibly at this rate if the arrival of the substitute is postponed, and (ii) the expected increase in scarcity λ as the underlying stock is depleted.

The indifference equation has a striking implication: when expectations are more pessimistic with respect to the remaining stock —a higher α— and when the consumer surplus $u(q)$ is strictly concave, then supplies maintaining the above-stated indifference increase; this can be seen from Fig. 2. This increasing compensation reflects the fact that the relationship becomes more costly to the consumer — an observation that we characterize in detail below.

It proves useful to define the maximal scarcity cost,

$$\lambda^* = \max_q \{ \frac{u(q) - \bar{u}}{q} \} = \frac{u(q^*) - \bar{u}}{q^*} \tag{9}$$

as the largest scarcity cost for the buyer such that it is possible to offer q^* and still entice continuation. If beliefs are so pessimistic that $\lambda > \lambda^*$, it immediately follows that no continuation stage can exist; the buyer immediately invests. On the other hand, if the belief implies that the seller's stock is so large that it will in all cases be left partially in the ground, then there is no scarcity cost $\lambda = 0$. Under this belief, continuation only requires the supply that provides the same surplus as the buyer's outside option, $q^I = \overline{q}$.

We can now express the buyer's indifference between continuation and investment as follows. Given supply offer q, and consistent beliefs s^L, continuation of the resource consumption pays the buyer the immediate surplus $u(q)$ above the substitute surplus $\overline{u}$. To be indifferent at supply q^I, the continuation payoff must equal the buyers stopping payoff. The following properties of the indifference supply will be instrumental in characterizing the equilibrium:

Lemma 1 *More pessimistic beliefs imply higher scarcity costs λ, and require a larger supply in (7): $\lambda = \lambda(s^L, \alpha)$ and $q = q^I(s^L, \alpha)$ are decreasing in s^L and increasing in α. Furthermore:*

(i) $\overline{q} \leq q^I(s^L, \alpha) \leq q^*$

(ii) *for all* $s > 0 : \lim_{\alpha \to 0} \lambda(s, \alpha) = 0$ *and* $\lim_{\alpha \to 0} q^I(s, \alpha) = \overline{q}$

(iii) *either* $\lambda(0, \alpha) < \lambda^*$ *and* $q^I(0, \alpha) < q^*$*, or there is some* $0 < s^* < kq^m$ *such that* $\lambda(s^*, \alpha) = \lambda^*$ *and* $q^I(s^*, \alpha) = q^*$*, and* $q^I(s, \alpha)$ *non-existent for smaller* $s < s^*$*.*

Proof. See Appendix. ■

In words, the required supplies increase in "pessimism" from levels that give no excess surplus over the substitute surplus ($\bar{q}$), arising when there is almost infinite reserve expectation, to the maximal surplus generating supply (q^*). The last item shows that, given the prior type distribution, we can either always find the belief s^L for the lowest type and the supply such that the buyer is indifferent, or such indifference-making supply exists only for sufficiently high beliefs for s^L.

2.4 Seller's strategy

Payoff at stopping: Consider the seller's payoff given that the buyer stops at t when the seller's (privately known) stock is s_t. Policy (1) over $[t, t+k]$ generates the overall payoff for the seller

$$V_t^I = V^I(s_t) = \begin{cases} k\pi(s_t/k) \text{ if } s_t < kq^m \\ k\pi(q^m) \text{ otherwise.} \end{cases} \tag{10}$$

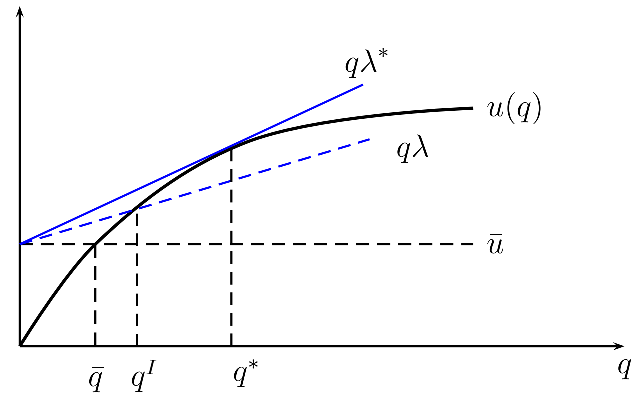

Figure 2: Determination of q^I and λ^*

As the stock declines, the scarcity cost of continuation becomes larger for the seller: the marginal value of the resource is $\kappa_t = V^{I\prime}(s_t)$ where

$$\kappa_t = \kappa(s_t) = \begin{cases} \pi'(s_t/k) \text{ if } s_t < kq^m \\ 0 \text{ otherwise.} \end{cases} \tag{11}$$

Continuation strategy: Given beliefs (s^L, α), the buyer requires a supply q^I to continue the resource relation. The buyer only invests if supplies fall short of q^I. We show that this strategy for the buyer implies that all sellers who have sufficient resources will pool their types by supplying q^I to keep the consumer precisely indifferent between stopping and investing. The seller will rationally decide whether to supply q^I, and for how long. Each seller knows its initial stock s_0 and so can choose an opt-out time $T = T_{s_0}$ for that stock level and supply path such that $q_t \geq q^I$ for all $t < T$. We can write the value of this program as

$$V(s_0) = \max_{\{q_t, T\}} \int_0^T \pi(q_t)dt + V^I(s_0 - Q_T), \tag{12}$$

where Q_t is the cumulative sum of the supplies at time t. We rewrite the integral in the objective by substituting supply as the variable,

$$\begin{aligned} V(s_0) &= \max_{Q_t} \int_0^{Q_T} \pi(q_t)/q_t dQ_t + V^I(s_0 - Q_T) \\ &= \max_{Q_t} \int_0^{Q_T} p(q_t)dQ_t + V^I(s_0 - Q_T) \\ &= p(q^I)q^I T + V^I(s_0 - q^I T), \end{aligned}$$

where the last line simply expresses the fact that by keeping supplies at the buyer's reservation level, $q_t = q^I$, the seller receives the reservation price for continuation for all units in its reserve, until stopping at T. The stopping time is found by the first-order condition

$$\begin{aligned} p(q^I) &= V^{I\prime}(s_0 - q^I T) \\ \Rightarrow \frac{\pi(q^I)}{q^I} &= \kappa(s_T). \end{aligned} \tag{13}$$

The left-hand side is the marginal change in the seller's continuation value, equalling the equilibrium price. The right-hand side is the marginal change in the seller's stopping value (11).

Separation strategy: We can see that that all sellers prefer stopping to continuation when their current stock falls below the quantity implied by (13). However, the buyer cannot tell how far the seller is from this critical stock level — there will be type revelation only at stopping: a seller who induces stopping at t will do by supplying post-stopping individually rational supply $q_t < q^I$ from which the buyer can infer how much the seller has and initially had of the resource.

Equation (13) thus defines the smallest seller type s^L that supplies q^I as a function thereof: $s^L = \sigma(q^I)$ in

$$\frac{\pi(q^I)}{q^I} = \pi'(\frac{s^L}{k}). \tag{14}$$

From this expression, and from the strict concavity of profits $\pi(.)$, we find the following properties:

Lemma 2 *Larger continuation supplies imply larger minimal resources in (14): $s^L = \sigma(q^I)$ is continuous, strictly increasing, $\sigma(0) = 0$, $kq^I > \sigma(q^I)$, and $\sigma(q^u) = s^m$.*

Figure 3 visualizes the Lemma. Moreover, the Figure shows a widening gap between the required supply q^I and the separation supply s^L/k, indicating that the supply disruption upon revelation of the seller's type increases with q^I. This property does not follow from the concavity of profits but it does hold when the marginal revenue drops faster for positive quantities than the price; then, we have

$$\frac{\partial[kq^I - \sigma(q^I)]}{\partial q^I} > 0. \tag{15}$$

We will invoke this assumption in the equilibrium characterization that we discuss next.

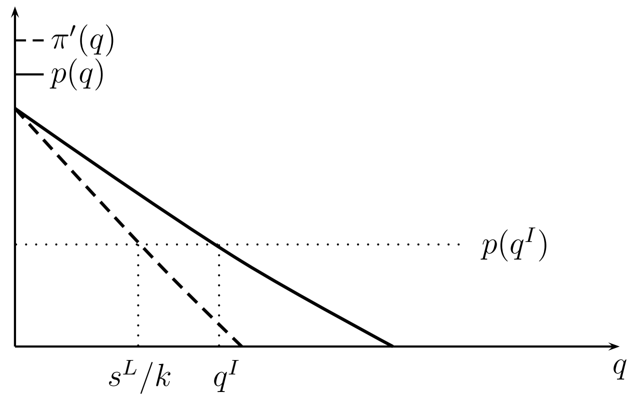

Figure 3: Required supply $q^I$and separation supply s^L/k.

3 Equilibrium resource relationship

We can now characterize the determinants of the equilibrium resource relationship. From the buyer's problem, we know that the buyer tolerates expected scarcity up to $\lambda^* = \mathbb{E}\hat{u}'(s/k)$ where λ^* is a given number defined by the buyer's primitive payoff expressions in (2). Continuation requires that the buyer trusts the relationship enough so that $\lambda < \lambda^*$. But, using the seller's incentives, the buyer can readily measure whether there can be enough trust in the relationship. The following results shows that there is a simple dichotomy that determines if there can be enough trust for continuation.

Theorem 1 *The stationary equilibrium resource relationship is described by*

- *continuation: if $\lambda(\sigma(q^*)) \leq \lambda^*$, then a unique pair of beliefs and supplies (s^L, q^I) exists that satisfies buyer's indifference (14) and seller's incentives (7), and $s^L < s^m$, $\overline{q} \leq q^I \leq q^*$.*
- *stopping: if $\lambda(\sigma(q^*)) > \lambda^*$, then for any s^L, it is optimal for the buyer to always invest.*

Proof. See Appendix. ■

The dichotomy is thus the following. The smallest type that complies with the buyer's largest conceivable supply requirement has stock $\sigma(q^*)$. This defines a pessimistic conjectural belief that allows the buyer to test whether the expected scarcity can in principle be less than what the buyer can tolerate. If yes, then the true equilibrium belief is actually more optimistic, and can be uniquely defined as well as the associated supply. Otherwise, the buyer's requirement and the sellers' incentives are incongruent, leading to immediate stopping. Later, we introduce shocks to the options outside the resource relationship, so that the incentive incongruence can arise later in time than $t = 0$.

3.1 Trust, dependence, and supply shocks in the relationship

We have noted in Lemma 1 that the buyer's requirement for supplies increases with pessimism as measured by α; this parameter measures both the expected scarcity, and the preciseness of the estimate that the actual stock has value at $s^L + 1/\alpha$. The equilibrium belief s^L tends to increase with pessimism, and this partially compensates the buyer. However, this compensation alone is not enough and the previously discussed feature carries over to the equilibrium: the buyer places less trust in the relationship when α is increased, and therefore requires larger supplies for compensation. A sufficient increase in pessimism must lead to ending of the relationship. The next Proposition summarizes these findings.

Proposition 1 *There is a threshold α^* such that for $\alpha = \alpha^*$ the unique stationary equilibrium satisfies $q^I = q^*$. For more pessimistic initial beliefs (higher α), no continuation equilibrium exists. For more optimistic initial beliefs (lower α), the equilibrium supply q^I decreases as α decreases.*

Proof. See Appendix. ■

Strikingly, the increase in scarcity leads to larger supplies rather than smaller as in standard exhaustible-resource theory (see, e.g., Dasgupta and Heal, 1979). The difference is explained by elements in our setting that introduce caution on the consumer side, that is, the buyer's necessary dependence on the resource through the time-to-build period, and also by strategic interactions that allow bribing for continuation through generous supplies. In addition to pessimism, the consumer-side caution and the required compensation can increase if the delays for bringing the substitute online become longer.

Proposition 2 *There is a threshold k^* such that for $k = k^*$ the unique stationary equilibrium satisfies $q^I = q^*$. For longer demand adjustment delays, no continuation can equilibrium exists. For shorter adjustment delays (lower k), the equilibrium supply q^I decreases as k decreases, reaching the buyer's outside option supply $q^I = \bar{q}$ for $k = 0$.*

Proof. See Appendix. ■

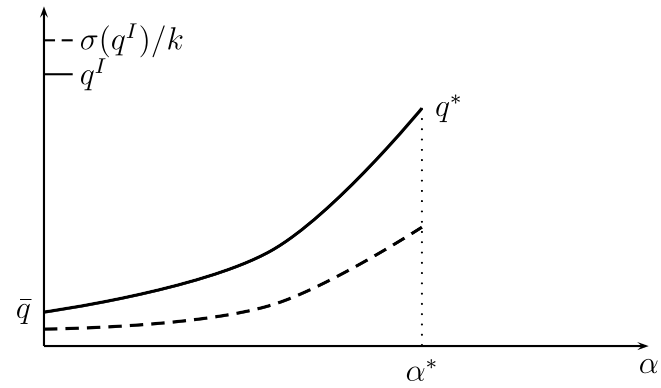

Figure 4: Pessimism (α), supply (q^I), and the expected supply shock ($q^I - \sigma(q^I)/k$).

Interestingly, when the buyer's outside option becomes readily available ($k = 0$), the buyer's share of the resource surplus vanishes; the surplus from supplies $q^I = \bar{q}$ is the same as without the resource. Thus, the inability to adjust demand immediately is the source of the buyer's bargaining power.

Proposition 3 *There is a threshold $\overline{u}^*$ such that for $\overline{u} = \overline{u}^*$ the unique stationary equilibrium satisfies $q^I = q^*$. For better substitutes, no continuation equilibrium exists. For worse substitues (lower $\overline{u}$), the equilibrium supply q^I decreases as $\overline{u}$ decreases, reaching the buyer's outside option supply $q^I = 0$ for $\overline{u} = 0$.*

Proof. See Appendix. ■

Figure 4 shows the relationship between pessimism (α) and the equilibrium supply but also the belief for the drop in supply ($s^L/k = \sigma q^I/k$) that follows follows the increasing pessimism; a similar figure could be presented for the relationship between supplies and the dependence period k. The Figure depicts an increasing expected supply disruption when the equilibrium supplies increase.

Proposition 4 *Increasing buyer side caution either through pessimism (α) or longer dependence interval (k) leads to a larger expected supply disruption in equilibrium, if (15) holds.*

This results follows directly from assumption (15) combined with the previous two Propositions.

3.2 Substitute shocks

The Proposition 3 signals that when $\overline{u}$ jumps from below to above $\overline{u}^*$, the buyer will decide to invest and potentially leave some resource unused in the ground. We briefly consider this case, assuming that there is constant hazard rate x that such an improved substitute will arrive. That is, we consider the economy when $\overline{u}^A < \overline{u}^*$, but moves with probability rate x into a state with $\overline{u}^B > \overline{u}^*$. Let W^B be welfare in the second state, immediately after investment. Assume that the buyer will know about the transition in the state of the substitute k time ahead, meaning that the improved substitute is directly availabe after the transition period when the buyer has not initiated the transition yet. The buyer's payoff after continuation becomes:

$$\begin{aligned} \mathbb{E}_t W_t &= \varepsilon[u(q_t) - \overline{u}] + \varepsilon hk[\hat{u}(s^L/k) - \overline{u}] + \varepsilon x \mathbb{E}_t W^B + (1 - \varepsilon h - \varepsilon x)\mathbb{E}_t W_t \Rightarrow \\ u(q^I) &= \overline{u}^A - x(\mathbb{E}_t W^B - \mathbb{E}_t W^I) + q^I \mathbb{E}_t[\hat{u}'(s_t/k)] \end{aligned}$$

where x^{-1} is the expected time before the improved substitute arrives, so that

$$\mathbb{E}W^B - \mathbb{E}W^I = \frac{1}{x}(\overline{u}^B - \overline{u}^A)$$

The potential arrival of a new substitute makes dependence less costly, and the buyer accepts a lower compensation: there is a positive probability that a better substitute arrives while depleting the resource, which makes the resource obsolete in practice.

$$u(q^I) = 2\overline{u}^A - \overline{u}^B + q^I \mathbb{E}_t[\hat{u}'(s_t/k)$$

Notice, though, that the arrival of the new substitute also affects the seller's payoff.

$$V(s_0) = \max_{T_s} \int_0^{T_s} e^{-xt}\pi(q_t)dt + \int_0^{T_s} (1 - e^{-xt})V^I(s_0 - Q_t)dt + V^I(s_0 - Q_{T_s})$$

subject to $q_t \geq q^I$. Yet, the first order conditions for the stopping time are precisely (13), so that $\sigma(q^I)$ remains the same. The new substitute arrival is exogenous to the seller's stopping decision and thus the seller's separation type is unchanged. This brings us:

Theorem 2 *If a new substitute for which no continuation equilibrium exists, $\overline{u}^B > \overline{u}^*$ arrives at hazard rate x, while for the current substitute a stationary continuation equilibrium exists, $\overline{u}^A < \overline{u}^*$, then supplies go up, prices go down, relative to the situation when no new substitute arrives. The economy moves to the stopping stage with a downwards supply shock when the seller's type becomes public. The economy moves to the stopping stage when the new substitute arrives. The supply shock is up (down) when the remaining stock is large (small).*

4 Discussion

We have made several modeling choices to make progress on a previously unexplored problem. There is a set of assumptions ensuring that the stationary equilibrium description is feasible. First, we imposed stationarity of beliefs ruling out dynamic signaling schemes that could potentially facilitate faster separation of types. Second, even when beliefs are stationary, the expected resource would decline, if we deviated from the exponential distribution for types, leading to a physical non-stationarity of the environment. We believe that the latter extension has a higher priority for the substance matter of this paper.[15]

Appendix: model of one-time interaction for alternative distributional assumptions Discounting

5 Concluding remarks

We started with an illustration from the past, the Chilean nitrate monopoly, which was ended by the buyer side action. Let us now close the plot by discussing implications in an other market where it may be the seller side that initiates the ending of the relationship: the market for conventional crude oil.

The ownership of the cheapest-to-extract oil reserve is extremely concentrated by any measure and concentration is expected to increase in the near future.[16] This concentration of ownership implies that strategic management of the conventional oil stocks is likely even without a formal cartel among producers. The conventional oil producers often engage in active "demand management", emphasizing credibility and security of supply. The resource that, for example, Saudi Arabia is controlling is unique in that it allows extraction of high quality output with relatively little capital investment. It also allows for rapid and large production rate changes. Reserves with such properties are at the heart of the economics of the oil dependence because, roughly put, the remainder of the fossil fuel supply is capital intensive and costly when used for the production of liquid fuels. In fact, it is this low-cost but finite reserve with concentrated ownership and inelastic short-run demand that is the exhaustible resource of interest; the rest of pro-

[15] In the setting of our stopping game, the equilibria building on non-stationary beliefs need not satisfy the buyer's indifference.

[16] See the "2007 Medium-Term Oil Market Report" published by the International Energy Agency for estimates of the Core OPEC reserves. The Saudi share of the Core OPEC stocks is expected to increase over time.

duction can be seen as part of substitute fuel production, including costly conventional oil sources, nonconventional oils, biofuels, and alternative energy sources.[17]

The industry experts estimates of the remaining viable core-oil stocks vary widely, which is a precondition for the equilibrium where the supply disruption is a possibility. Moreover, we have observed increasing supplies from such core sources over time, although the stocks are undisputedly declining. (to be continued)

We conclude by discussing some properties of the approach chosen. Recall that the adjustment delay of demand is what makes the buyer's bargaining position to improve over time. Thus, while intuition suggests that the adjustment delay is costly to the buyer, it delivers a surplus share to the buyer in equilibrium. Letting k to vanish implies that the buyer's outside option arrives immediately on adoption, and the seller needs to compensate the buyer only for delaying the substitute by a marginal unit of time. This implies that the buyer receives the long-run payoff during the resource consumption period, and thus no resource surplus. This is an instance of Coase conjecture; the buyer's resource-share vanishes at the twinkling of an eye as expressed by Coase for the durable-good monopoly. It is important to emphasize that the Coase conjecture arises from the seller's ability to wait for the buyer's outside option price (substitute price). In this sense, our framework is different from Hörner and Kamien (2004), where there is no substitute but the conjecture arises due to increasing extraction costs for the resource. Liski and Montero (2009) show that the substitute utility alone is enough for the Coase conjecture to arise in the resource model, if discounting is absent and the resource market does not die out at the arrival of the substitute. Under positive discounting, the conjecture does not arise but the buyer and the seller share the surplus depending on the relative sizes of the resource and substitute utility. In the current framework, the distortions and a sharing of the resource surplus arise even in the absence of discounting because the substitute has the infrastructure interpretation.

[17] There are different definitions of conventional and nonconventional oils, and these also change over time; see the Hirsch Report (prepared for the U.S. Department of Energy, 2005). The report emphasizes that the important scarcity is in the reserves of high-quality conventional oil.

Appendix

The buyer's strong long-run average payoff

Consider the following expected discounted stopping payoff

$$\mathbb{E}U^I = \int_0^k \int_{s^L}^{\infty} [\hat{u}(s/k)] f(s) e^{-\rho\tau} ds d\tau + e^{-\rho k} \frac{1}{r} \bar{u}$$

where $\rho > 0$ is the discount rate. Define

$$\mathbb{E}W^I = \mathbb{E}U^I - \frac{1}{r}\bar{u}.$$

Letting $r \to 0$, gives the buyer's nondiscounted payoff (2) in the text. This is the strong long-run average payoff, as defined by Dutta (1991). The conditions stated in Dutta (1991) for this payoff criterion to identify the appropriate policies for the undiscounted limit are trivially satisfied in our setting.

Proof of equivalence in (4)

Exploiting the exponential distribution's properties, such as $f'(s) = -\alpha f(s)$, and $f(s^L) = \alpha$, we have

$$\begin{aligned}
\mathbb{E}_t[\hat{u}'(s_t/k)] &= \int_{s^L}^{\infty} k\hat{u}'(s_t/k) f(s_t) ds_t, \\
&= -\int_{s^L}^{\infty} k[\hat{u}(s_t/k) - \overline{u}] f'(s_t) ds_t + [k[\hat{u}(s_t/k) - \overline{u}] f(s_t)]_{s^L}^{\infty} \\
&= \alpha\{\mathbb{E}_t W_t^I - k[\hat{u}(s^L/k) - \overline{u}]\}
\end{aligned}$$

Now, when we substitute $h = \alpha q$, we have (4).

Lemma 1

Proof. From concavity of $\hat{u}(q)$, we have that $\lambda = \mathbb{E}\hat{u}'$ is decreasing in in s^L and increasing in α and the last part of the lemma. The proof that q^I increases in λ is provided by Gerlagh and Liski (2011). ■

Proposition 1

Proof. Let q run from $\overline{q}$ to q^*, and define $s^A = \sigma(q)$ and s^B implicitly through $q = q^I(s^B, \alpha)$. Both s^A and s^B are continuous in q. For $q = \overline{q}$, $s^A = \sigma(\overline{q}) < k\overline{q}$, and $s^B = kq^m$

so that $s^A < s^B$. For $q = q^*$, we have, $q^I(s^B, \alpha) = q^*$, so $\lambda(s^B, \alpha) = \lambda^*$, and as $\lambda()$ decreasing in s, from $\lambda(\sigma(q^*)) \leq \lambda^*$, it must follow that $s^A = \sigma(q^*) \geq s^B$. Thus, there is some q with $\overline{q} \leq q \leq q^*$ for which $s^A = s^B$. Given the monotonicity of σ and λ, the equilibrium is unique. Similarly, from $\lambda(\sigma(q^*)) > \lambda^*$, it must follow that $s^A = \sigma(q^*) < s^B$ and no continuation equilibrium can exist. ■

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