Incomplete information and resource dependence

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Abstract

When should a buyer of an exhaustible resource move to a substitute if only the seller knows the exact size of the remaining resource stock? We characterize stationary dynamic signalling equilibrium of this Coasian bargaining problem, and find that adjustment delays in ending the relationship and the degree of asymmetric information shape the equilibrium outcome. The Coase conjecture —the informed agent takes all the surplus— arises when adjustment delays vanish. Under sufficient informational asymmetry, the model describes increasing supplies followed by a supply shock as an equilibrium phenomenon. The pattern arises from small sellers' incentive to over-supply in order to postpone the buyer's decision to end the relationship.

JEL Classification: D4; D9; O33; Q40.

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1 Introduction

The dependence on exhaustible resources is among the most pressing economic and political concerns of our times. In this paper, we focus on strategic interactions between consumers and suppliers of an exhaustible resource, and ask the following simple question: if an importing party (buyer) of the resource does not observe the size of the seller's

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resource reserve, when should the buyer develop and adopt a substitute? Does the seller's private information lead to distortions in the sales and timing of the buyer's move to the substitute? No answers to these questions can be found from the literature, and yet they seem quite important for understanding how policies dealing with oil dependence, or even climate change, should be designed.

One framework for thinking about the resource dependence is provided by the theory of durable-goods monopoly, building on the conjecture presented by Coase (1972). In the Coasian framework, the monopolist supplies durable goods and is confronted with a ceiling on cumulative demand as the market saturates. The connection to exhaustible resources has been long recognized (see, e.g., Maskin and Newbery,1990; Karp and Newbery 1993), and made explicit in Hörner and Kamien (2004) and Liski and Montero (2009). In the resource context, the monopolistic supplier becomes a policy maker representing the consumers and caring about the consumer surplus. The limits to cumulative demand in the durable good case translate to limits on cumulative supply in the exhaustible resource model. This conceptual connection between the two theories—durable-good monopoly and exhaustible-resource monopsony—provides a basis for thinking about the resource dependence issue as a Coasian bargaining problem between the importing party and the supplier of the exhaustible resource.

We develop a two-agent version of the resource bargaining problem under incomplete information, add an element that we find essential for resource dependence: the buyer's ability to adjust demand. In general, the ability to adjust demand depends on the knowledge of substitute technologies but also on other properties of buyer's demand infrastructure such as the capital intensity. The ease with which the buyer can move away from the resource to substitute supplies will shape the equilibrium and surplus sharing in our model. In the literature, the substitute acts as a"backstop", so called by Nordhaus (1973) who first considered the effect of the implied price caps on current resource prices. The backstop is traditionally conceptualized as an instantly available technology (see Dasgupta and Heal 1974, 1979), but adjustment delays are obviously reasonable. Recent research has developed a multi-sector description of the resource substitution process such that the transition is gradual as sectors move to substitutes at different times (Chakravorty, Roumasset, and Tse 1997). We capture this element through a time-to-build delay that, as explained below, is critical to the equilibrium outcome.

The substitute provides an outside option for the buyer but, because of its time-to-build delay, the value of this option changes over time as the continued resource depletion increases the possibility of serious resource scarcity during the forthcoming transition period. We find that as the resource is depleted, the costs of continued dependence increase, and as a consequence the buyer demands a larger compensation for not moving away from the resource. That is, the continued resource dependence forces the seller to supply larger quantities over time to postpone the demand change. The strategic implications of the substitute development thus reverse the basic implications of the Hotelling (1931) model where supplies necessarily decline with the remaining resource stock. In our earlier paper, Gerlagh and Liski (2008), we find that this implication of the time-to-build delay arises also under complete information.

In the current paper, we focus on the implications of incomplete information. We find that the buyer's improving bargaining position over time, arising from the time-to-build delay and resource depletion, creates a role for asymmetric information: if the actual resource stock is small compared to the buyer's beliefs, the seller will have an incentive to "over-report" by supplying levels that maintain the buyer's beliefs of a larger stock. However, when the actual resource reserve sufficiently decreases ultimately, the seller prefers not to maintain these beliefs, but will reveal the true scarcity to best exploit the buyer's time-to-build constraint for the substitute. After sufficient depletion of the privately known small stock, it therefore becomes individually rationally for small sellers to reveal their type and trigger the buyer's action through a supply shock. The model thus describes increasing supplies followed by a supply shock as an equilibrium outcome. It also shows how asymmetric information can delegate the timing of the demand change to the informed party, that is, to the seller, who initiates the change through the revelation of true scarcity.

Conceptually our work relates closely to the work on Coase conjecture, and its connection to resources. As this literature, we are interested in eliminating bargaining frictions by assuming high-frequency transactions, and then we wish to study the resulting determinants of surplus shares. When discounting is absent, and the buyer's substitute becomes instantaneously available (no time-to-build delay), the seller captures the entire surplus from resource consumption, establishing the Coase conjecture in the relationship. It is thus clear that our main results follow from the adjustment delay in the demand change. This source of commitment power to the strategic agent is similar, in spirit, as production smoothing in the durable-good theory (Kahn 1986; see also Mc Afee and Wiseman 2008) — the buyer receives a surplus share due to consumption smoothing considerations.

However, in one important respect our work departs from a typical durable-good problem where the uninformed agent makes repeated offers to the informed agent whose valuation is private information (see, e.g., Gul et al. 1986). 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 signalling, and thus leads to multiplicity of sequential equilibria (Fudenberg and Tirole 1983; see also Ausubel et al., 2002), it has the at least two clear advantages.

The first advantage is that the stationary limiting equilibrium without informational asymmetry converges to the unique Markov-perfect equilibrium that preserves an interesting sharing of surplus. Thus, as opposed to typical two-agent Coasian bargaining situations, the limiting complete information outcome does not collapse to an outcome where one party takes all the surplus. This allows us to make a distinction between the determinants of the equilibrium outcome that relate to the complete and incomplete information environments such as the time-to-build delay and the degree of informational asymmetry in the relationship.

The time-to-build delay determines surplus sharing under complete information, but it also determines if there is a role for asymmetric information — without any adjustment delay, the asymmetric information does not matter in the relationship as the seller will be able implement his first-best outcome. On the other hand, the degree of informational asymmetry, measured as the preciseness of the buyer's estimate of the seller's stock, determines whether it is the informed (seller) or uninformed (buyer) agent who initiates the switch to the substitute. In the other words, when the asymmetry in information is small there is a dynamic pooling equilibrium where the buyer never learns the seller's type before investment, and it is public information when the investment takes place. This equilibrium is not substantially different from the complete information outcome. When the asymmetry is large, there is a dynamic separating equilibrium where small sellers will signal their type by a supply shock. Conditional on not observing such shocks, the buyer will learn the seller's type by consuming. The equilibrium timing of investment is seller's private information, and therefore there is genuine aggregate uncertainty regarding the termination of the relationship.

The second advantage of the dynamic signalling approach is that it allows a market interpretation of the bargaining process, as long as there is an agent coordinating actions on the strategic variable on both sides of the market. For the buyer side, it is the government deciding the infrastructure investment making the resource obsolete, and for the seller side, it is a cartel coordinating sales. Otherwise, trading takes place through the resource market. This interpretation would be difficult to achieve under a structure where the uninformed agent takes initiative in screening the informed agent as in the informed principle case (see Maskin and Tirole, 1992).[1]

As to the connection between resources and durable-goods, our paper is the first to consider the sequential equilibrium under incomplete information.[2] Hörner and Kamien (2004) consider the formal connection between the two theories under full commitment. Liski and Montero (2009) show that the connection to durable goods breaks down under the assumption that the final value of the resource is determined by the cost of the (inexhaustible) substitute supply. In the current paper, we assume in contrast with Liski and Montero (2009) that there is a time-to-build delay for the substitute and that the resource market dies out once the substitute is in place. This is motivated by our current interest to study the implications of a substitute that has an infrastructure nature, while Liski and Montero study the traditional, instantly available, substitute.

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. In Section 3, we start by analyzing equilibrium under constant beliefs, i.e., when the buyer does not learn about the seller type by consuming the resource. This is the simplest possible case for introducing the framework, and it is directly useful for defining the maximum degree of asymmetry in the relationship that can support an equilibrium without a surprise supply shock, analyzed in Section 3.4. When the degree of asymmetry is sufficiently large, we find the equilibrium outcome discussed above: the resource consumption path involves a risk of a supply shock revealing the seller's true type. We conclude in Section 4 by discussing the connection to Coase conjecture, and the sources of distortions and surplus shares. Throughout, we describe the equilibria in the un-discounted limit, firstly, to simplify exposition, and, secondly, to illustrate that the nature of strategic interaction is robust, i.e., it is preserved in the no-discounting limit.

[1]Deneckere and Liang (2006) consider screening, which is more natural in their case since there is no market involved.

[2]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.

2 The Model

2.1 Basic assumptions and notation

There are two agents, the buyer and the seller of an exhaustible resource. The buyer's flow payoff from consuming the resource is given by function

$$u : \mathbb{R}_+ \mapsto \mathbb{R}_+$$

where $u(q)$ is assumed to be increasing, continuous, and nonlinear in consumption q. The seller's flow payoff from selling the resource is given by function

$$\pi : \mathbb{R}_+ \mapsto \mathbb{R}_+$$

where $\pi(q)$ assumed to be strictly concave and continuously differentiable in q. Payoffs u and π are connected through the consumer's utility function

$$\tilde{u} : \mathbb{R}_+ \mapsto \mathbb{R}$$

such that $u(q) = \tilde{u}(q) - \tilde{u}'(q)q$ and $\pi(q) = \tilde{u}'(q)q$. Let $q^m = \arg\max \pi(q)$ and define $Z = [0, q^m]$. We assume further that the buyer's payoff u is either strictly concave or convex on Z.

The buyer is thus an agent whose payoff is the consumer surplus $u(q)$ (e.g., government). The seller is a resource monopoly. Time t is discrete, extends to infinity, and each period lasts ε units of time (we define the game for $\varepsilon > 0$ but characterize the limit $\varepsilon \to 0$). At each t, the buyer has a binary choice variable, $d \in \{0, 1\}$, where $d = 1$ indicates that the buyer terminates the relationship with the seller. At each t, the seller's only choice variable is supply $q \in \mathbb{R}_+$.

At any t, the game can be in one of the three main states, denoted by $I \in \{CS, IS, LS\}$. State CS is the continuation state that prevails if and only if the buyer has not chosen $d = 1$ in the history of the game. State IS is the interim state where the buyer has already chosen $d = 1$ but the substitute for the seller's supply has not yet arrived. We assume that state IS lasts k units of continuous time, counting from the point in time where $d = 1$. State LS is the long-run state where the substitute is in place. The substitute makes the resource obsolete and generates some surplus utility flow $\bar{u}$ to the buyer satisfying $\bar{u} < u^m \equiv u(q^m)$. State LS lasts forever. Thus, the choice $d = 1$ causes the transition from CS to IS and, after k units of time, from IS to LS.

The initial resource stock size is a random variable $s_0 \in [s_0^L, s_0^H]$. The seller's cumulative sale over time cannot exceed the initial stock. We assume that the informed agent (the seller) observes s_0 while the uninformed agent (the buyer) knows only the distribution of s_0. It proves useful to describe the buyer's belief at t by two parameters (σ_t, θ_t) where σ_t is the expected resource stock and θ_t is the spread of the belief such that $[s_t^L, s_t^H] = [\sigma_t - \theta_t, \sigma_t + \theta_t]$. We will use both notations interchangeably.

2.2 Strategies and equilibrium

If the buyer has the belief (σ_t, θ_t) in state $I = CS$, his payoff from choosing $d_t = 1$ can be written in continuous time as follows

$$U^I(\sigma_t, \theta_t) = \mathbf{E}_{s\in[\sigma_t-\theta_t,\sigma_t+\theta_t]} \int_0^k u(q_\tau^s)e^{-r\tau}d\tau + e^{-rk}\frac{\overline{u}}{r}, \tag{1}$$

where q_τ^s is the anticipated supply of seller type s at each τ over k units of time when the buyer is still dependent on the seller. The first expression on the right is the payoff from state IS, and the second part is the payoff from state LS.

If the game moves from CS to IS at t, then all seller types have k units of time to go at t, i.e., they die after state IS. Type s_t will maximize profits over the time interval k, and this determines a supply path q_τ^s together with the overall payoff

$$V^I(s_t) = \int_0^k \pi(q_\tau^s)e^{-r\tau}d\tau. \tag{2}$$

All strategic interaction takes place in state CS, understanding the above-defined payoffs for states IS and LS. To describe the strategies, we can therefore focus on the case $I = CS$. We consider discrete time intervals of length ε, and then analyze the continuous-time limit. At the start of time interval t (i.e., period t), the buyer inherits the prior from the previous period (σ_t, θ_t); in the first period $t = 0$, the prior is given by (σ_0, θ_0). If $I = CS$ at t, we assume the following stages:

1. The seller offers supply q_t;

2. The buyer updates beliefs to (σ'_t, θ'_t), and decides on investment $d_t \in \{0, 1\}$;

3. If the buyer does not invest, $d_t = 0$, markets clear at q_t for the timespan $[t, t+\varepsilon]$ and the game stays in state $I = CS$. If the buyer invests, $d_t = 1$, the strategic interaction stops and the payoffs (1) and (2) are realized.

The appropriate equilibrium concept is sequential equilibrium in behavioral strategies, and we look for a stationary equilibrium (see Ausubel et al. 2002 for the definition). Note that the informed and uninformed parties make decisions within a period but the informed party moves first. The assumption of stationarity restricts the buyer's belief of the seller's type to be a simple left truncation of the prior which is uniform in our case. The concept also implies that the equilibrium strategies are Markovian, i.e., they depend only on the current belief (σ_t, θ_t), independently of the history leading to this belief.[3] Finally, we are interested in belief structures that involve no built-in threats: the information of the seller's type will be revealed by a continuous improvement of the prior (σ_0, θ_0).

Under these assumptions, the equilibrium will develop as a stationary Markov process. We suppress the state I, as all strategic interaction takes place in $I = CS$, and consider the state space as

$$S = \{(s_t, \sigma_t, \theta_t) \in \mathbb{R}^3_+; 0 \leq \sigma_t - \theta_t \leq s_t \leq \sigma_t + \theta_t\}.$$

We will construct a mapping $\Omega_\varepsilon : S \mapsto S$ for the change of the state in equilibrium when time moves from t to $t + \varepsilon$. The equilibrium is explicitly defined for $\varepsilon > 0$, but we will characterize the continuous-time limit $\varepsilon \to 0$. The equilibrium path is thus described using differential methods.

We can describe the buyer's action by an acceptance function $\eta(\sigma_t, \theta_t)$, describing the outcome of the first two stages as follows. The buyer accepts the offer if it is is at least equal to $\eta(\sigma_t, \theta_t)$, and chooses $d = 0$ otherwise. The acceptance function may not exist at all, a case in which the buyer chooses $d = 0$ irrespective of the seller's offer. On the equilibrium path, the buyer will remain indifferent between the continued resource use ($d = 0$) and investment ($d = 1$), until the acceptance function ceases to exist. Therefore, the uninformed party's (buyer's) indifference condition drives most of

[3]See Maskin and Tirole (2001) for the definition of the Markov-perfect equilibrium. Note that stationarity requirement is stronger than Markov perfection in our case; see Ausubel et al. 2002.

the dynamics in equilibrium as long as dependence continues. We will observe that under these assumptions, the seller will never supply more than $\eta(\sigma_t, \theta_t)$ but small sellers may deviate downwards, if it is in their interest that the buyer invests.

Since we limit the set of possible equilibria to exclude those where out-of-equilibrium offers lead to a violation of the skimming property (see Fudenberg and Tirole 1995 for the property), we can describe the updating of beliefs by a continuous truncation function $\zeta(\sigma_t, \theta_t)$, with the same domain as the acceptance function. Small sellers $s_t < \zeta(\sigma_t, \theta_t)$ will find it profitable to trigger investment by supplying below $\eta(.)$. Thus, not observing such a supply truncates the distribution from the left.

Let us now pull together the time-line as follows.

Type selection. Nature selects the resource level $s_0 \in [\sigma_0 - \theta_0, \sigma_0 + \theta_0]$. We assume that the initial level is sufficiently large so that no seller type will trigger investment, $\zeta(\sigma_0, \theta_0) < s_0^L = \sigma_0 - \theta_0$.

Continued dependence with pooling The seller offers $q_t = \eta(\sigma_t, \theta_t)$, and the buyer does not invest. As long as the smallest seller type exceeds the truncation value, $\zeta(\sigma_t, \theta_t) < \sigma_t - \theta_t$, the buyer will not learn about the type and beliefs are constant, $\theta_t = \theta_0$, while the true resource and the mean develop according to $\frac{ds_t}{dt} = \frac{d\sigma_t}{dt} = -q_t$. This stage can end in two ways: (i) the buyer invests (acceptance function $\eta(\sigma_t, \theta_t)$ becomes undefined); or (ii) small sellers find it individually rational to trigger investment (type support drops below the truncation value $\zeta(\sigma_t, \theta_t) \geq \sigma_t - \theta_t$). The latter case means that we enter the phase of continued dependence with separation.

Continued dependence with separation During this phase, beliefs are continuously updated to maintain $\zeta(\sigma_t, \theta_t) = \sigma_t - \theta_t$. Small sellers reveal themselves, while large sellers continue to supply $q_t = \eta(\sigma_t, \theta_t)$. This stage continues until a small seller type triggers investment, $s_t \leq \zeta(\sigma_t, \theta_t)$, or the buyer invests ($\eta(\sigma_t, \theta_t)$ becomes undefined).

Post-investment. If buyer invests at $t = T$, then from $t = T$ to $t = T + k$ the seller offers the profit maximizing $q_t^{s_T}$.

It proves useful to focus on two cases. First, the informational asymmetry is small when $\theta_0 \leqslant \theta^*$, where the critical spread θ^* is defined shortly. In this case, the equilibrium progresses from type selection to pooling, and finally to the buyer's decision to invest.

Second, if the informational asymmetry is large, $\theta_0 > \theta^*$, then the type selection is necessarily followed by a phase of separation. We start by considering the small informational asymmetry case.

3 Equilibrium

3.1 Buyer's indifference under pooling

Under pooling of types, the buyer's beliefs are constant, which means that $\frac{d\sigma_t}{dt} = -q_t$, and $\theta_t = \theta_0$. For this reason, we drop the time index from θ in this section. However, we keep θ in the acceptance function and in related expressions, because at a later stage, we need to find a critical θ^* such that when $\theta_0 \leq \theta^*$ the equilibrium without updating of beliefs on θ exists.

The equilibrium under consideration requires that the buyer is indifferent between accepting the seller's offer and investing. Continuation without investment is costly because the buyer's dependence period of length k remains the same but the expected stock for future consumption declines. The seller's offer must therefore compensate the buyer for the delay. This compensation requirement can be derived from the buyer's indifference: the expected overall consumer surplus from delayed investment must at least be as high as from immediate investment $U^I(\sigma_t, \theta)$, as defined in (1). The marginal value of the resource to the buyer at the time of investment is readily defined as

$$\lambda(\sigma_t, \theta) = U^I_\sigma(\sigma_t, \theta).$$

We can express the buyer's indifference between continuation and investment as follows.

Lemma 1 *The buyer's acceptance function $q_t = \eta(\sigma_t, \theta)$ satisfies*

$$u(q_t) = rU^I(\sigma_t, \theta) + q_t\lambda(\sigma_t, \theta). \tag{3}$$

When $r \to 0$, this equation becomes

$$u(q_t) = \overline{u} + q_t\lambda(\sigma_t, \theta). \tag{4}$$

Equation (3) has a simple interpretation. To be indifferent between investment and a delay, the buyer requires a compensation that is equal to the interest on the overall consumer surplus plus the decrease in the asset value, measured from the buyer's perspective. Without discounting, $r = 0$, the surplus from consuming q_t and not investing should cover the cost from postponing the arrival of the substitute utility $\overline{u}$ by one marginal unit of time plus the cost from depleting the expected resource, captured by the term $q_t\lambda(\sigma_t, \theta)$.

For the proof of Lemma 1, consider a time interval of length ε. The buyer does not update $\theta_t = \theta_0$ by assumption, and $\sigma_{t+\varepsilon} = \sigma_t - \varepsilon q_t$. By definition, when the buyer is indifferent between investment and continuation, $U^I(.)$ describes the overall consumer surplus before as well as immediately after investment. The supply level q_t that is required to keep the buyer indifferent satisfies the dynamic programming equation

$$U^I(\sigma_t, \theta) = \varepsilon u(q_t) + e^{-r\varepsilon}U^I(\sigma_t - \varepsilon q_t, \theta), \tag{5}$$

where $e^{-r\varepsilon}$ is the continuous-time discount factor. For ε sufficiently small, we can approximate the equation as

$$0 = \varepsilon u(q_t) - \varepsilon r e^{-r\varepsilon}U^I(\sigma_t, \theta) - \varepsilon q_t U^I_\sigma(\sigma_t, \theta), \tag{6}$$

which gives (3). Without discounting, the consumer surplus becomes infinite and, therefore, we will adopt a long-run average payoff criterion.[4] Substract the long-run payoff from U^I, and denote the resulting payoff as W^I:

$$W^I(\sigma_t, \theta) = U^I(\sigma_t, \theta) - \frac{\overline{u}}{r}. \tag{7}$$

Function W^I thus measures the expected value of the excursion above (or below) the long-run payoff at the time of investment. We now rewrite the arbitrage condition (3) in terms of the excursion welfare W^I defined in (7). Notice that $U^I_\sigma(\sigma_t, \theta) = W^I_\sigma(\sigma_t, \theta) = \lambda(\sigma_t, \theta)$ so that we get

$$u(q_t) = \overline{u} + rW^I(\sigma_t, \theta) + q_t\lambda(\sigma_t, \theta), \tag{8}$$

which gives (4) in the limit $r \to 0$. This completes the proof of Lemma 1.

We assume $r = 0$ from now on, and exploit (4) together with the uniform prior to describe the acceptance function $\eta(\sigma_t, \theta)$. Note first that the left-hand side of (4) is bounded in q while the right-hand side is linear in q for given λ. We can therefore define

$$\lambda^* = \max_{q \leq q^m}\{\frac{u(q) - \overline{u}}{q}\} \tag{9}$$

as the largest marginal value of the resource to the buyer such that (4) can hold.[5] We denote the associated supply by q^*, i.e.,

$$\lambda^* = \frac{u(q^*) - \overline{u}}{q^*}. \tag{10}$$

[4]See Dutta (1991) for discussion of the long-run average payoff criterion.

[5]The seller will not supply more than q^m so we can limit the domain to $Z = [0, q^m]$

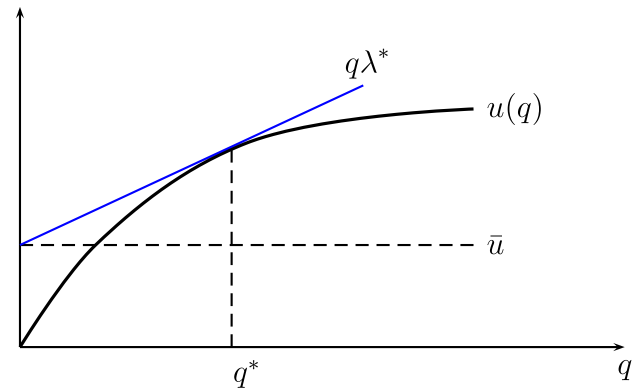

Figure 1: Determination of λ^*

as the largest marginal value of the resource to the buyer such that (4) can hold. For all $\lambda \leq \lambda^*$, it is possible to find a supply that keeps the buyer indifferent between continuation and investment, and thus the acceptance function exists. In contrast, for $\lambda > \lambda^*$, the marginal value of the resource to the buyer after investment always exceeds the marginal value under continuation (there is no supply level satisfying (4)), and it is always in the buyer's interests to invest. Figure 1 illustrates the definition of λ^* for a concave surplus.

To describe the domain over which the acceptance function is well defined, we define the critical expected stock level $\sigma^* = \sigma^*(\theta)$ as the level at which the marginal value of the resource to the buyer reaches its maximum:

$$\lambda(\sigma^*, \theta) = \lambda^*. \tag{11}$$

Consider then the values that $\eta(.)$ can reach. When the resource has no marginal value to the buyer, then $\lambda(\sigma_t, \theta) = 0$ and, by (4), $u(q_t) = \overline{u}$. We denote the implied lower bound for supply by $q_t = \overline{q}$. The supply level q^* associated with the highest buyer's marginal value of the resource turns out to be the upper bound for the acceptance function.

Lemma 2 *Assume constant $\theta_t = \theta > 0$, and that $u(q)$ is either strictly concave or convex on $Z = [0, q^m]$. Then the acceptance function*

$$\eta : [\sigma^*, \infty] \times \theta \mapsto [\overline{q}, q^*]$$

is continuous, strictly decreasing in σ for $\sigma < kq^m + \theta$, with $\eta(\sigma^*, \theta) = q^*$, and $\eta(\sigma, \theta) = \overline{q}$ if $\sigma \geq kq^m + \theta$.

Proof. See Appendix A. ■

To explain the result, note first that for $\sigma > kq^m + \theta$ all seller types would be above the monopoly type $s = kq^m$, and in this case there would be no expected scarcity. Sellers would (after investment) not supply above the monopoly supply q^m at each time point and, thus, when investment occurs, the sellers would leave some stock unused. This in turn implies that $\lambda = 0$ in (4), and the acceptance function does not change with the stock. Before investment, the seller will only compensate for the delay in the arrival of the substitute and supply $\overline{q}$.

To focus on the interesting case, consider $\sigma < kq^m + \theta$ so that there is expected scarcity. As the stock declines, the scarcity cost of continuation becomes larger and the supply must be increased to compensate the buyer for continuation. More precisely, when $r = 0$, after investment the seller will maximize the value of the resource by spreading the remaining stock evenly over the k time window. This together with a uniform prior implies that the aggregate consumer surplus is

$$W^I(\sigma_t, \theta) = \int_{\sigma_t - \theta}^{\sigma_t + \theta} \frac{1}{2\theta} \widehat{u}(s/k) ds - k\overline{u}, \tag{12}$$

where we use a capped consumer surplus function $\widehat{u}(s/k) = u(\min\{s/k, q^m\})$, as seller types $s > kq^m$ will not supply above the monopoly level q^m. The marginal value of the resource, $W^I_\sigma = U^I_\sigma = \lambda$, is now

$$\lambda(\sigma_t, \theta) = \frac{k}{2\theta} [\widehat{u}(\frac{\sigma_t + \theta}{k}) - \widehat{u}(\frac{\sigma_t - \theta}{k})]. \tag{13}$$

From this expression we can see that that the scarcity cost of continuation increases as the expected stock declines, as long as there is expected scarcity (see Appendix for the full analysis).[6]

By

$$d\sigma_t/dt = -q_t, \tag{14}$$

and Lemma 2, the acceptance function defines an increasing supply path as a function of time. Thus, for any $\sigma_0 > \sigma^*$ the indifference-making supply increases over time until the expected stock reaches $\sigma_t = \sigma^*$. At this point, $\lambda_t = \lambda^*$ and $q_t = q^*$, and the buyer must invest as his indifference cannot be sustained further.

[6]For clarity, we note that the domain for the acceptance function is nonempty: $\lambda^* > 0$ as we can fill in q^m in (9) with $\bar{u} < u^m$. Notice also that λ is continuous in σ_t, as defined in (13), and is zero for $\sigma_t > kq^m + \theta$.

3.2 Seller's pooling equilibrium strategy

In this section, we will describe the distribution (σ_t, θ) such that all seller types within (σ_t, θ) prefer to supply $q_t = \eta(\sigma_t, \theta)$ as defined in Lemma 2. It is intuitively clear that small seller types may prefer investment to continued dependence as they may run out of the stock to follow the buyer's indifference supply. From this observation, we will deduce a critical informational asymmetry θ^* such that when the initial asymmetry is less, $\theta_0 \leq \theta^*$, all seller types will prefer continued dependence until the buyer decides to invest.

Given the concave profit function and zero discounting, the seller will maximize post-investment profits by supplying at a constant level if investment decision is made at stock level s_t. We can thus define

$$V^I(s_t) = \begin{cases} k\pi(s_t/k) \text{ if } s_t < kq^m \\ k\pi(q^m) \text{ otherwise.} \end{cases} \tag{15}$$

Denote the equilibrium value of the resource to the seller before investment by $V(s_t, \sigma_t - s_t, \theta)$. The bias in beliefs $\sigma_t - s_t$ remains constant as long as beliefs are not updated $\theta_t = \theta_0$ (recall that we consider an equilibrium without updating). We wish to explore conditions under which all seller types prefer to supply $\eta(\sigma_t, \theta)$ as defined Lemma 2 rather than the post-investment supply. That is, for all seller types we must have

$$V(s_t, \sigma_t - s_t, \theta) \geqslant V^I(s_t) \tag{16}$$

throughout the state CS.

Lemma 3 *There exists finite $\theta^* > 0$ such that for all $\theta \leqslant \theta^*$ condition (16) is satisfied for all seller types $s_t \in [\sigma_t - \theta, \sigma_t + \theta]$.*

Proof. See Appendix B. ■

The proof builds on the observation that complying with the buyer's acceptance supply becomes increasingly costly to all sellers over time. The gap between continuation and stopping $V(s_t, \sigma_t - s_t, \theta) - V^I(s_t)$ closes continuously along the depletion path $q_t = \eta(\sigma_t, \theta)$, determining some cumulative supply after which the smallest seller prefers stopping over continuation. Conversely, for the cumulative supply after which the buyer demands $q_T = q^*$, there exists some seller type for which the indifference between continuation and stopping holds. If we denote this type's stock at T by $s^{\min}$, we can see that the critical spread θ^* must satisfy

$$\sigma^*(\theta^*) = s^{\min} + \theta^*. \tag{17}$$

When $\theta \leqslant \theta^*$, all seller types prefer to comply with the buyer's demand on the equilibrium path.

3.3 Pooling Equilibrium

We can now describe an equilibrium under small informational asymmetry.

Theorem 1 *For $\theta \leq \theta^*$, the resource depletion path given by the acceptance function $q_t = \eta(\sigma_t, \theta)$ defined in Lemma 2 is an equilibrium.*

Proof. By construction, the buyer is indifferent along this path (Lemma 2). No seller type gains by triggering the buyer's investment (Lemma 3). We have assumed out-of-equilibrium beliefs supporting a stationary acceptance function. For example, the buyer may preserve the prior when observing a supply above $q_t = \eta(\sigma_t, \theta)$ — under this assumption, supplying more than the indifference supply would not benefit any seller type, and supplying less leads to investment. Other out-of-equilibrium beliefs are also possible. ■

The equilibrium has some interesting properties.

Supplies increase over time. We have already described in Lemma 2 that the indifference-making supply has to increase over time to compensate the buyer for the increased scarcity.

Investment date is common knowledge. The relationship is terminated by the buyer; given (σ_0, θ_0), the cumulative depletion $\sigma_0 - \sigma^*$ before investment is known to all parties.

Symmetric information limit is obtained as $\theta \to 0$. When the informational asymmetry disappears, the equilibrium converges to that analyzed in Gerlagh and Liski (2008). The incomplete information equilibrium thus converges to the unique (symmetric information) Markov-perfect equilibrium.

Adjustment delay determines the sharing of the resource surplus. If $k \to 0$, then $\lambda(\sigma, \theta) \to 0$ from (13), and the buyer's indifference becomes $u(q) = \overline{u}$. The buyer will receive only the long-run surplus, and no excursion above it, meaning that the full resource surplus goes to the seller.

For the last item, note that the seller maximizes the social surplus achievable from the resource when $k = 0$, independently of his private information. This is a version of the Coase conjecture consistent with Hörner and Kamien (2004), and Liski and Montero (2009), who both analyze the conjecture in the resource context.

3.4 Equilibrium with separation

We consider now informational asymmetry large enough, $\theta_0 > \theta^*$, to rule out the equilibrium where the acceptance function is based on pooling of all seller types. We may say that there is separation of types because some sellers do not want to comply with the acceptance function but rather trigger investment.[7] We denote the set of possible beliefs in this equilibrium by

$$B = \{(\sigma, \theta) | \sigma^*(\theta) \leq \sigma, \theta^* \leq \theta \leq \sigma\}, \tag{18}$$

where the inequalities have the following meaning: the first ensures the existence of the acceptance function; the second ensures that separation occurs; and the last ensures a non-negative support for the seller types.

The spread θ_t is now a variable, as the buyer will update the belief on the seller's type. However, for given (σ_t, θ_t) the buyer's equilibrium acceptance supply is determined by the same expressions as before, i.e., the indifference between continuation and investment still satisfies equation (4) independently of how the belief (σ_t, θ_t) was reached. We can rewrite this indifference condition as

$$u(q_t) = \bar{u} + q_t \frac{k}{2\theta_t}[\widehat{u}(\frac{\sigma_t + \theta_t}{k}) - \widehat{u}(\frac{\sigma_t - \theta_t}{k})]. \tag{19}$$

The following Lemma is a straightforward extension of Lemma 2.

Lemma 4 *Assume $\theta_0 > \theta^*$ and that $u(q_t)$ is either strictly concave or convex. Then, indifference (19) defines an acceptance function*

$$\eta : B \mapsto [\overline{q}, q^*]$$

where $\eta(\sigma, \theta)$ is continuous and strictly decreasing in σ for $\sigma < kq^m + \theta$.

That the acceptance supply is strictly decreasing in σ follows from point-wise application of Lemma 2 on $[\theta^*, \theta_0]$.

[7] On the other hand, it may be equally appropriate to say that there is screening of types by the buyer because the equilibrium satisfies the skimming property by the stationarity assumption.

To explain the equilibrium transition $\Omega_\varepsilon(s_t, \sigma_t, \theta_t)$, we first assume the existence of a truncation function $\zeta(\sigma_t, \theta_t)$, and then we derive it. Consider $(s_t, \sigma_t, \theta_t) \in S$. If $s_t < \zeta(\sigma_t, \theta_t)$, it follows that the seller will offer less than $\eta(\sigma_t, \theta_t)$; otherwise $\zeta(.)$ would not be a truncation function. The buyer will then invest, and the equilibrium will move to the post-investment phase. If $s_t \geq \zeta(\sigma_t, \theta_t)$, the seller will supply $q_t = \eta(\sigma_t, \theta_t)$, given that supplying more leaves only extra surplus to the buyer without influencing beliefs (stationarity assumption). After observing that the seller complies, the buyer will rule out the small seller types with $s_t < \zeta(\sigma_t, \theta_t)$. The mean and spread are updated as follows:

$$(\sigma_t', \theta_t') = (\frac{1}{2}[\sigma_t + \theta_t + \zeta(\sigma_t, \theta_t)], \frac{1}{2}[\sigma_t + \theta_t - \zeta(\sigma_t, \theta_t)]), \tag{20}$$

implying that after ε units of time, the state transition is

$$(s_{t+\varepsilon}, \sigma_{t+\varepsilon}, \theta_{t+\varepsilon}) = (s_t - \varepsilon q_t, \sigma_t' - \varepsilon q_t, \theta_t'). \tag{21}$$

Let us then consider the equilibrium path from the largest seller's point of view, i.e., consider the seller type who has initially stock of size $s_0 = \sigma_0 + \theta_0$. It is common knowledge that this seller type will not trigger investment in equilibrium. If this was not the case, the equilibrium truncation could in principle exhaust the types, and conditional on reaching the largest type, the buyer would know that the seller has less than needed to satisfy the buyer's indifference — by the definition of θ^*, there is an interval of seller types that prefer to supply q^*, and therefore the equilibrium truncation must stop at $\sigma^* - \theta^*$. We can therefore consider a counterfactual equilibrium path $(\widetilde{\sigma}_t, \widetilde{\theta}_t, \widetilde{q}_t)$ without separation following if the seller type is sufficiently large. Conversely, each seller type sufficiently small will prefer to depart from the counterfactual path at some time point. To describe these small types, we consider the payoff of a small type along the counterfactual path: for an arbitrarily small period length ε, each small seller type can find the optimal opt-out time $T_s < T$ by solving

$$\max_{T_s < T} \int_0^{T_s} \pi(\widetilde{q}_t) dt + V^I(s_0 - \int_0^{T_s} \widetilde{q}_t dt), \tag{22}$$

where T denotes the time where the buyer's indifference can no longer be sustained. The interior first-order condition is

$$\frac{\pi(\widetilde{q}_{T_s})}{\widetilde{q}_{T_s}} = V^{I\prime}(s_{T_s}). \tag{23}$$

The left-hand side is the marginal change in the seller's continuation value along $(\widetilde{\sigma}_t, \widetilde{\theta}_t, \widetilde{q}_t)$, equalling simply the equilibrium price at T_s. The right-hand side is the marginal change in the seller's stopping value. If, in equilibrium, supplies $\widetilde{q}_t$ go up, so that prices go down, then the left-hand side is decreasing in t while the right-hand side is increasing in t. Thus, either the left-hand side exceeds the right-hand side for all $t \leq T$, in which case it is optimal for the seller type to supply η_t throughout until the buyer invests, or there is a unique $T_s \leq T$ for which the equality is satisfied. We can rewrite the seller's indifference condition for stopping using equilibrium supply $\eta(\sigma, \theta)$, truncation function $\zeta(\sigma, \theta)$, and the expression for stopping payoff (15) as follows

$$\frac{\pi(\eta(\sigma,\theta))}{\eta(\sigma,\theta)} = \pi'(\frac{\zeta(\sigma,\theta)}{k}). \tag{24}$$

We can construct the truncation function $\zeta(.)$ from this expression, and find the following properties:

Lemma 5 *Assume $\theta_0 > \theta^*$ and that $u(q_t)$ is either strictly concave or convex. Then, if $d\eta(.)/dt > 0$, indifference (24) defines a truncation function*

$$\zeta : B \mapsto [0, kq^*]$$

where $\zeta(\sigma, \theta)$ is continuous and strictly decreasing in σ for $\sigma < kq^m + \theta$.

Continuity of $\zeta(.)$ follows from continuity of $\eta(.)$, combined with the assumption that $\pi(.)$ is continuously differentiable and strictly concave. We now have defined the acceptance function and the truncation function, and we have seen how these two together determine the dynamics of the stock and beliefs through $\Omega_\varepsilon(.)$ for ε arbitrarily small.

Theorem 2 *For $(\sigma_0, \theta_0) \in B$, the supply path defined by Lemma 4 and the truncation path defined by Lemma 5 constitute an equilibrium.*

Proof. By construction, the buyer is indifferent along the path and the seller's separation is well-defined, provided supplies increase over time along the counterfactual path $(\widetilde{\sigma}_t, \widetilde{\theta}_t, \widetilde{q}_t)$. We show that supplies increase by contradiction. Assume that supplies decrease over consecutive arbitrarily closely located time points t and $t+\varepsilon$. By continuity of η and ζ, the construction of the truncation function ζ implies that $\zeta_t > \zeta_{t+\varepsilon}$. But, then $\eta_t > \eta_{t+\varepsilon}$, because otherwise the buyer's indifference cannot hold. This is the contradiction.
The same out-of-equilibrium beliefs support this equilibrium as in the small informational asymmetry case. ■

Also this equilibrium has some interesting properties.

The timing of investment is private information. Only the seller knows if there is enough stock to continue until the buyer decides to invest.

There is a persistent possibility of a supply shock. As soon as truncation starts, the non-continuing seller types cease to comply with the buyer's demand η_t by a discrete downward jump in supply, $\hat{s}_t^L/k < \eta_t$.

4 Concluding remarks

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.

5 Appendix A: Lemma 2

Proof. As explained in the main text, when the support for types lies entirely above kq^m, then even the smallest type has too much stock to be exhausted if investment is made at current expected stock σ. In this case, $\lambda(\sigma, \theta) = 0$, and the seller can satisfy the arbitrage condition with q_t such that $u(q_t) = \overline{u}$.

When $\sigma < kq^m + \theta$, there is expected scarcity. Assume this for the rest of the proof. The proof that $\eta(.)$ is decreasing in σ is separate for concave and convex $u(q)$.

Strictly concave $u(q)$. By $\sigma \geq \sigma^*(\theta)$ there exists a solution q to (4). That is, by construction of $\sigma^*(\theta)$, $\lambda \leq \lambda^*$ and we can find q satisfying

$$u(q) = \overline{u} + q\lambda.$$

Differentiating with respect to q and λ, yields

$$\begin{aligned} u'(q)dq &= \lambda dq + qd\lambda, \text{ or} \\ \frac{dq}{d\lambda} &= \frac{q}{u'(q) - \lambda}. \end{aligned}$$

We obtain $dq/d\lambda > 0$ for $\lambda < \lambda^*$ and thus for $\sigma > \sigma^*(\theta)$. Concavity and the choice of the lowest q for which (4) holds ensures that $q < q^*$, and thus $u' > \lambda$ for $\lambda < \lambda^*$. A higher shadow price of the resource implies a higher indifference-making supply level. Now, we only need to show that $\lambda_\sigma(\sigma, \theta) < 0$ to demonstrate the result. Recall

$$\lambda(\sigma_t, \theta) = \frac{k}{2\theta}[\widehat{u}(\frac{\sigma_t + \theta}{k}) - \widehat{u}(\frac{\sigma_t - \theta}{k})],$$

and note that either (i) $\widehat{u}(\frac{\sigma+\theta}{k}) - \widehat{u}(\frac{\sigma-\theta}{k}) = u^m - u(\frac{\sigma-\theta}{k})$ decreases in σ due to the fact that $u(\frac{\sigma-\theta}{k})$ is increasing (part of the support below kq^m), or (ii) $\widehat{u}(\frac{\sigma+\theta}{k}) - \widehat{u}(\frac{\sigma-\theta}{k}) = u(\frac{\sigma+\theta}{k}) - u(\frac{\sigma-\theta}{k})$ decreases in σ due to concavity (full support below kq^m). Thus, $\eta(\sigma, \theta)$ is decreasing in σ.

Strictly convex $u(q)$. The desired result follows from the item (i) above if we can show that the case (ii) is not feasible. But this follows from the fact that $q^* = q^m$ when $u(q)$ is convex. Under convex surplus, the supply q^* is at the boundary of feasible supplies (see Figure 2). If the full support is below kq^m, the post-investment supply is below q^m for sure, and the buyer strictly prefers investment. On the other hand, if the full support is above kq^m, then the indifference-making supply is given by $u(q) = \overline{u} < u^m$ where the inequality was assumed at the outset (the monopoly supply is more than enough for the indifference when there is no scarcity). By these two extremes, it follows that $\sigma^*(\theta)$ is defined by

$$\lambda^* = \frac{k}{2\theta}[u^m - u(\frac{\sigma^*(\theta) - \theta}{k})] \tag{25}$$

so that part of the support must be below kq^m when the buyer's indifference breaks down. For $\sigma \geq \sigma^*(\theta)$, the supplies are then increasing by the argument given for the concave utility case (i). ■

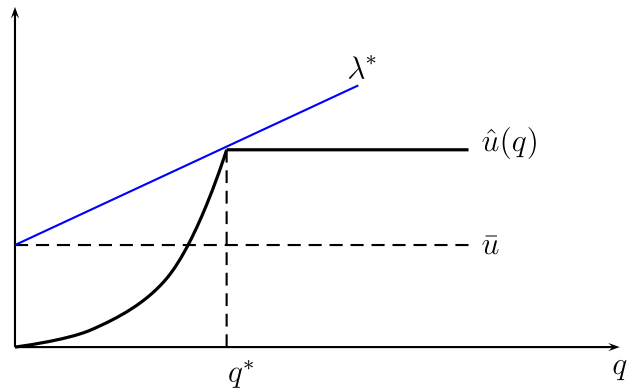

Figure 2: Determination of λ^* under convex surplus

6 Appendix B: Lemma 3

Proof. To prove the lemma, we construct the maximum spread θ^* such that, at the point of investment T with $q_T = q^*$, the smallest seller type is indifferent between continuation and stopping. We then show that if the spread is larger, then the smallest seller type would prefer stopping before T, and if the spread is smaller, then no seller type prefers stopping over continuation along the entire path $t \leq T$.

Consider a short period length ε. Without investment, we have

$$V(s_t, \sigma_0 - s_0, \theta) = \varepsilon\pi(q_t) + V(s_t - \varepsilon q_t, \sigma_0 - s_0, \theta), \tag{26}$$

where $q_t = \eta(\sigma_t, \theta)$ is defined by Lemma 2. The first-order approximation gives

$$0 = \varepsilon\pi(q_t) - \varepsilon q_t V_s. \tag{27}$$

We can therefore conclude that along the path before investment, when beliefs are constant, the marginal value of the stock to the seller is simply its price,

$$V_s(s_t, \sigma_t - s_t, \theta) = \frac{\pi(\eta(\sigma_t, \theta))}{\eta(\sigma_t, \theta)} = p_t. \tag{28}$$

Notice that as supplies go up, prices go down along the arbitrage supply path (Lemma 2), so that the marginal value of the resource to the seller decreases over time. To the seller, the marginal value of the stock after investment is

$$V^{I\prime}(s_t) = \max\{0, \pi'(s_t/k)\}, \tag{29}$$

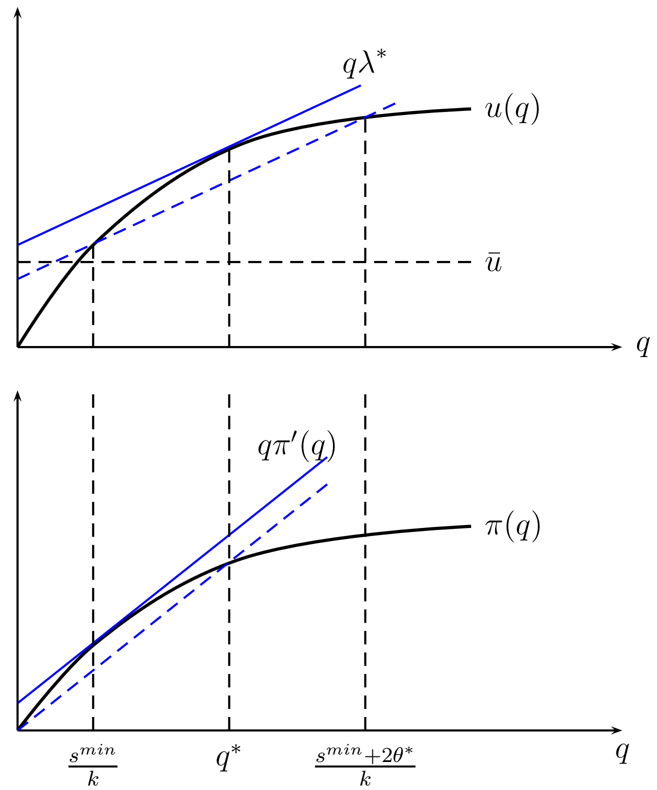

Figure 3: Construction of θ^* for a concave surplus

which ultimately goes up as the stock depletes. Now we consider the time of investment where the buyer demands q^*. For the seller to be also indifferent at this point, he must have a stock of size $s^{\min}$ satisfying $V_s = V^{I\prime}(s^{\min})$, or

$$\pi'(s^{\min}/k) = \frac{\pi(q^*)}{q^*}. \tag{30}$$

The strict concavity of $\pi(.)$ ensures that $s^{\min} < kq^*$ exists. Sellers with larger stock $s_t > s^{\min}$ would prefer to continue without investment because for these types $V_s = p > V^{I\prime}(s) = \pi'(s/k)$. Sellers with a stock smaller than $s^{\min}$ would have triggered investment at earlier time points. To define the spread for which both the buyer and the seller are indifferent at T, we note that θ^* must satisfy

$$\sigma^*(\theta^*) = s^{\min} + \theta^*. \tag{31}$$

The value for the maximum spread θ^* is constructed from the following equation:

$$\lambda^* = \frac{k}{2\theta^*}[\widehat{u}(\frac{s^{\min} + 2\theta^*}{k}) - \widehat{u}(\frac{s^{\min}}{k})]. \tag{32}$$

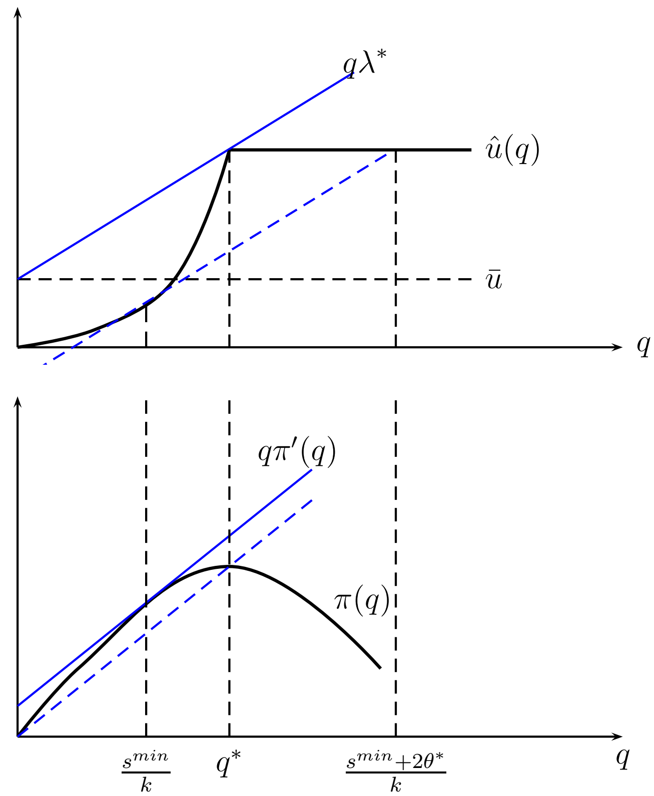

Figure 4: Construction of θ^* for a convex surplus

Figure 3 illustrates the construction of θ^* for a concave surplus; see Figure 4 for the convex surplus case.

Finally, we need to show that when the spread falls short of the maximum spread, $\theta_0 \leq \theta^*$, then (16) is satisfied throughout the equilibrium path. This follows from the observation that $V = V^I$ at $t = T$, and V_s decreases while $V^{I\prime}$ increases going backwards in time (increasing s_t). This ends the proof of the lemma. ■

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