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Private Storage of Common Property*

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Résumé

Il est souvent le cas qu'une ressource en propriété commune puisse, une fois extraite, êtr accumulée sous forme de stock privé plutôt que d'être écoulée immédiatement sur le marché. Nou nous penchons dans ce texte sur cet aspect jusqu'à maintenant négligé du problème de propriét commune. Nous y analysons les effets positifs et normatifs de l'existence de la possibilité de stockag privé de la ressource commune. La possibilité de privatiser la ressource commune en la stockant une fois extraite va, dans certains cas, éliminer les inefficacités attribuables à la propriété commune. Dans d'autres cas, par contre, elle va les exacerber, même quand la vitesse d'extraction n'a pas d'effet négatif sur le taux de récupération du stock.

Une fois le stockage commencé, le rythme d'accumulation va s'accélérer jusqu'à l'épuisement du stock. Dans des cas limites, ces accumulations spéculatives sont instantanées. Elles sont alors semblables aux "attaques spéculatives" qui ont déjà été étudiées dans le contexte de ventes par un gouvernement de stocks tampons dans le but de soutenir un prix plafond et qui ont été par la suite appliquées au marché des changes étrangers. Nous montrons que si la taille des réserves initiales de la ressource commune est inconnue, il pourra en résulter des attaques spéculatives répétées. Dans le cas des ressources en propriété commune, ces attaques spéculatives auront lieu naturellement, sans intervention exogène. Mais il se peut que certaines politiques gouvernementales déclenchent de telles attaques en créant des contraintes de type propriété commune. Nous montrons que la précipitation des pêcheurs pour remplir dès le début d'une saison de pêche un quota global qui leur aurait été imposé peut être vue comme une attaque spéculative.

Mots clés: Ressource non renouvelable, propriété commune, stockage, attaque spéculative, quota de prise global.

Abstract

This paper examines a characteristic of common property problems unmodeled in the published literature: extracted common reserves are often stored privately rather than sold immediately. We examine the positive and normative effects of such storage. Privatization of common reserves through storage may eliminate inefficiencies altogether but the premature extraction involved may also exacerbate them—even if rapid extraction does not reduce ultimate recovery.

Once storage commences, accumulation accelerates until extraction ceases. In limiting cases, these speculative acquisitions are instantaneous and are identical to the "speculative attacks" first studied in the literature on government sales from bufferstocks to defend price ceilings and then applied to the foreign exchange market. As shown here, if the size of underground reserves in the common is unknown initially, repeated speculative attacks may result. In the case of common properties, these speculative attacks arise even under *laissez faire*. Alternatively, government policies can trigger them by creating a common-property constraint. We show that the precipitous filling of total catch quotas early in a fishing season, which often follows the imposition of such quotas, can be viewed as a speculative attack.

Keywords: Nonrenewable Resource, Common Property, Storage, Maximum Efficient Rate of Extraction (MER), Speculative Attacks, Total Catch Quotas.

1 Introduction

If a valuable natural resource is discovered to which anyone can claim ownership simply b extracting it, a free-for-all inevitably develops. Private storage facilities are often hastil cobbled together to capture extracted oil. Ise (1926) recounts the frenzied spectacle whic replayed itself across the United States. One photograph of a "storage facility" in Arkansas reprinted in Ise's volume, typifies scenes everywhere. It depicts a field 34 acres in area flooded with oil 50 feet deep in places. O'Connor (1958, p.345) emphasized the monumental waste which resulted:

> One of the results of the unhampered application of this rule [of capture] was the production into open tanks and earthen pits of oil far in excess of the market demand or the capacity of transportation facilities. This resulted in aboveground waste as much of this aboveground storage was lost by seepage and leakage, fire, overflowing of storage due to failure properly to operate wells or filling of the earthen pits by rain, breaking of levees and evaporation of the volatile liquids to the air...

Nontechnical discussions of extraction under free access such as those of Ise, O'Connor, and Prindle (1981) routinely emphasize the importance of aboveground storage as the vehicle for transforming common to private property. It is therefore surprising that such storage plays no role in any of the analytical treatments of common property extraction.[1]

The economics literature on the subject dates back to Gordon's (1954) analysis of extraction under free access. He hypothesized that if entry was free, the aggregate rate of extraction at any instant would increase to the point where all profits are dissipated. Given this instantaneous aggregate rate of extraction and assuming he knew the rate of biological growth of a stock of any size, Gordon was able to trace the evolution of the common reserve from its initial level onward.

[1]In their important empirical analysis of common property extraction, Libecap and Wiggins (1984) also emphasized the importance of aboveground storage but did not address the phenomenon analytically.

Negri (1990) provided some game-theoretic justification for Gordon's non game-theoretic analysis. He examined the Markov-perfect equilibrium of a multistage game where a finite number of players simultaneously extracts at each stage a renewable common pool resource[2]. He then analyzed aggregate extraction behavior as the number of players increased without bound, confirming in his particular example Gordon's hypothesis of complete rent dissipation. Brooks et. al. (1996), however, pointed out the existence of less benign examples where, if growth of the resource is sufficiently rapid, the non game-theoretic and game-theoretic approaches yield different predictions. Fortunately, they then formulated a condition *sufficient* for the two approaches to yield the same predictions. Given their result, Gordon's non game-theoretic approach can be used with confidence in lieu of the less tractable game-theoretic approach when analyzing the free-access equilibrium of any nonrenewable resource or indeed of resources growing at moderate speed.

In none of these models is storage above ground permitted. Instead, *everything* extracted from the common must be *marketed* immediately. Our purpose in this paper is to introduce aboveground storage into a free-access model like Gordon's so as to examine its positive and normative effects.[3] Our analysis is also closely related to Hotelling's (1931) seminal article since the equilibrium behavior of owners of aboveground stocks resembles that of foresighted extractors of private underground reserves.

Several insights emerge from our analysis. To say, as O'Connor does in the passage quoted above, that storage occurs *because* more is extracted than can be marketed confuses

[2] In this regard, he followed earlier analyses by Levhari and Mirman (1980), Eswaran and Lewis (1982), and Reinganum and Stokey (1985) of the Markov-perfect equilibria of multistage games of common property. Unlike Negri, however, these authors restricted their attention to the case of "restricted access". On the other hand, Cheung (1970) and Dasgupta and Heal (1979), like Negri, examined the free-access limit of a restricted-access game; however, the games they analyzed were static.

[3] As we were completing our preliminary draft, a working paper appeared by Kremer and Morcom (1996), which was motivated by the poaching from common property in Africa and the subsequent private storage of elephant tusks and rhino horns. Theirs is a highly valuable complement to our analysis since it focuses on two issues which have no counterpart in our nonrenewable case: multiple equilibria and the possibility of avoiding extinction equilibria.

causality.[4] As we show, it is the *opportunity* to store which *causes* more to be extracted than can be sold. Other things equal, extraction would not proceed at so rapid a pace if storage were infeasible. One additional feature of oil extraction, also uniformly neglected in the literature reviewed above, must be borne in mind: extraction exceeding a certain speed (the so-called maximum rate of efficient production or MER) *reduces* what can ultimately be recovered (McFarland, 1976). Despite the merits of private ownership and increased technological opportunities, there are thus several reasons why the opportunity to store when combined with the legal right to own what is extracted may paradoxically lower social welfare.[5]

Herfindahl (1967) showed that if two privately-owned pools of oil are extracted under constant marginal costs, then in a competitive equilibrium the pool with the strictly lower marginal cost will be exhausted before extraction of the higher cost oil commences. If the two extraction costs are identical, the source of extraction at any point in time is indeterminate. When one of the two pools is common property, however, these results change. We find that if each pool has the same constant marginal cost, the common must be entirely drained before any extraction of the privately-owned pool; and this postponement of any extraction from the private pool may also occur if that oil is strictly cheaper to extract.

We also discover a similarity between the frenzied phase during which oil from the commons is extracted and put in private stockpiles and the frenzied phase known in the literature as a speculative attack. The attacks which have been analyzed so far are responses to governments' attempts to maintain price ceilings by sales from bufferstocks or to maintain fixed

[4]The same confusion arises in Prindle (1981, p.24): "In addition, although oil must be quickly produced under unregulated conditions, it cannot necessarily be sold as quickly, *so it is stored*" [our emphasis].

[5]Tornell and Velasco (1992) is an interesting complement to our analysis. They examine a differential game model of common property extraction under restricted access, which they use to explain capital flows from poor countries with high rates of return but weak property rights to rich countries with lower rates of return but secure property rights. They ask whether the opportunity to transfer capital from the "common" to the secure country raises welfare in equilibrium. We ask the same question about the opportunity to transfer common reserves into aboveground storage. The two models differ in important ways, however. In our model assets grow at the *same* rate (zero) whether they reside above or below ground. Moreover, the transfer from the common to storage (or any other destination) is costly.

exchange rates by sales from foreign exchange reserves.[6] In contrast, the attack on a common property—and there may be multiple attacks if the initial reserve size is uncertain—can occur in the absence of any government intervention.

Alternatively, policies having nothing to do with price stabilization schemes can also trigger speculative attacks. In the final section of the paper, for example, we consider the effects of seasonal cumulative catch limits used to regulate fisheries. Such a limit constitutes a constraint on the cumulative extraction not merely of each individual fisherman but of the *collection* of fishermen. The quota thus is identical to the exhaustion constraint on a common property resource studied in previous sections. If such a policy constrained the purchasers of an ordinary produced good which could be stored, it would induce them to act like the extractors of an exhaustible resource which is common property. Recalling our previous analysis, we predict that the cumulative catch quota will be filled gradually until a certain date after which the remaining quota will be filled instantaneously (or very rapidly). The fish harvested in the attack on the quota are, of course, not all marketed immediately; some are frozen for subsequent resale. In reality, attacks on catch quotas have occurred days after the fishing season opened.

The paper proceeds as follows. In section 2, we examine the free-access equilibrium when storage is feasible and there exists an underground reserve which is common property. We begin by assuming that all underground reserves are common property but then permit there to be private underground reserves as well. Section 3 concerns social welfare. In that section, we first relax the assumption — maintained throughout section 2 — that the speed of extraction has no effect on ultimate recovery and compare the free-access equilibrium to the social optimum both with and without the opportunity to store. We then ask whether

[6] Salant and Henderson (1978) initiated this literature with their analysis of government attempts to peg the price of gold. Salant (1983) generalized their earlier analysis to uncertainty in the context of a stochastic harvest model. Krugman (1979) translated Salant-Henderson's result to an international finance context. The subsequent literature is vast. See Dornbusch (1987), Krugman and Obstfeld (1991), Flood and Garber (1994) and the references therein. Robert Flood and Nancy Marion will soon complete the most up-to-date survey.

the availability of a storage technology is socially beneficial when captured common property is regarded under law as private property. Section 4 shows that our results, when suitably reinterpreted, can explain market responses to cumulative catch limits. Section 5 concludes the paper.

2 How Access to Aboveground Storage Affects the Free Access Equilibrium

> "The best place to store oil until you need it is in God's reservoir where He put it and kept it for millions of years until man was given the intelligence to find it"—General Ernest Thompson [Texas Railroad Commissioner from 1932-65] as quoted in O'Connor (1958), p. 346

Our model has four types of agents: (1) consumers, (2) owners of private underground reserves, (3)stockpilers, and (4) extractors of common property under free access. Throughout, we assume that each of these market participants takes current and future prices as given and acts in his self interest. In a competitive equilibrium, the price path induces suppliers of the resource to satisfy market demand at every moment. To begin, we briefly review the well-known results of Hotelling (1931), Gordon (1954) and others concerning optimal behavior of each agent under perfect forsight.

Optimal behavior of "consumers" is summarized in their exogenous demand curve. The demand curve at time t is assumed to be a strictly decreasing, stationary function of the price at time t and to depend on no other prices. For simplicity, we assume that there exists a "choke price," below which demand is positive and above which it is zero. The demand curve can be taken to represent the optimal choice, at any given price, of a final consumer with quasilinear utility on the one hand or the optimal input choice of a firm which purchases the resource and uses it to produce output on the other hand.[7]

[7]See the appendices of Salant (1983) for details.

Optimal extraction by a private owner of underground reserves requires that he (1) utilize all of his reserves eventually and (2) extract in such a way that the marginal profit (the price net of the marginal cost) of extracting an additional barrel in present value terms be the same whenever extraction is strictly positive; when extraction is zero, the present value of the marginal profit must be smaller.

If the discounted wealth of stockpilers is maximized, all stockpiles must eventually be liquidated since prices are strictly positive and decumulation of aboveground stocks is assumed costless. Given any upward jump in a price path, it is optimal for stockpilers to purchase at an infinite rate for subsequent resale. More generally, purchasing at an infinite rate would be optimal if the percentage rate of increase in the price exceeded the rate of interest. On the other hand, it is optimal for stockpilers to hold zero inventories if price jumps down or, more generally, if the price rises in percentage terms by less than the rate of interest.

Following Gordon (1954), we assume that free access to a common property drives the extraction rate up until the average cost of extraction from the common pool equals the market price $p(t)$ and all rents are dissipated. Under free access, the average cost curve is in effect the "aggregate supply curve" of the common property extractors until reserves run out, after which their supply at any price is zero.[8]

The requirement that the optimal behavior of these four types of agents be *consistent at every moment* uniquely determines the equilibrium price path (for prices below the choke price) in each of the situations we examine. Our goal will be to predict and then evaluate normatively the equilibrium behaviors of each agent when aboveground storage is feasible and overly rapid extraction may diminish ultimate recovery.

But to illustrate equilibrium analysis in its simplest context, suppose for the moment that aboveground storage is impossible and ultimate recovery is unaffected by the speed of

[8] Alternatively, one can regard the average cost of extraction from the oil field as a function not merely of aggregate extraction but also of the remaining reserves; under this interpretation, the average cost curve jumps up when the common is depleted and coincides with the vertical axis.

extraction; in addition, assume that the only underground reserves are common property. In that situation, there will be positive demand at prices below the choke level and this demand can be satisfied only by extraction from the common property. Accordingly, the price must remain constant at the point where the demand curve intersects the average cost curve. Once the commons are completely drained, the price must then jump up to choke off demand.

This scenario would constitute a competitive equilibrium in the absence of the ability to store since (1) no agent can do strictly better at the equilibrium prices by alternative behavior and (2) market demand is satisfied at every instant. But if agents could store as private property aboveground stocks extracted from the common, it would not be an equilibrium. For, in that situation, foresighted agents would attempt to make *infinite* purchases immediately before the price jump for resale after the jump. Since the supplies do not exist to satisfy this infinite demand, the scenario we are describing cannot be an equilibrium.

2.1 No Private Underground Reserves

When storage is possible, the equilibrium price path must have no upward jumps. Moreover, when inventories are held above ground the price must rise by the rate of interest.[9] Given these considerations, the *equilibrium* price path must be composed of two phases. During the first, the real price is constant at a level which causes extraction at each instant to match demand so that no stocks accumulate. Denote this level p^*, the vertical component of the point where the demand curve ($D(p)$) cuts the aggregate extraction schedule ($AC^{-1}(p)$). During the second phase, the price grows from p^* at the rate of interest until demand is choked off. Given this rate of price increase, people would just be compensated, in the

[9] For simplicity, we assume that storage is costless and that 100% of each stored barrel can be retrieved. The passage from O'Connor in section 1, however, emphasizes that only a *fraction* of what was stored could in fact be retrieved. Suppose a fraction δ of what remains in storage is lost through leakage, seepage, fire or evaporation at each instant t. Then the price which would make someone indifferent between selling initially and storing until t would have to be increased to $P(t) = P(0)e^{(r+\delta)t}$. Hence, to take account of such losses, simply replace the exogenous real interest rate in our analysis by $r + \delta$.

absence of storage costs, for the interest they forego in holding aboveground inventories.

The second phase itself must be composed of two intervals. During the first, extraction exceeds demand (since $p > p^*$, $AC^{-1}(p) > D(p)$) and the excess is added to private stockpiles. Indeed extraction must increase over time since the price is rising and the extraction schedule ($AC^{-1}(p)$) is upward-sloping; moreover, since the demand curve ($D(p)$) is downward-sloping, less is consumed as time passes; for both reasons, additions to storage increase over time. If this situation persisted until the choke price was reached, however, it would clearly be a disequilibrium since the accumulated stocks would never be re-sold and it would have been more profitable not to buy them. What prevents the continual accumulation of stocks is the exhaustion of the common reserves. At precisely the moment when reserves disappear and extraction jumps down to zero, decumulation of aboveground stocks jumps up to replace it. Consequently, no discontinuity in the price path results. In the second interval, private inventories are decumulated to satisfy market demand until the choke price is reached.[10]

This constitutes an equilibrium because market demand is satisfied at every instant and each agent's behavior is optimal: the consumers are on their demand curve at all times; the extractors of the common property are on their aggregate "supply curve"; and the stockpilers are behaving optimally by (1) postponing their activities until the phase when the price rises at the rate of interest and (2) liquidating their stocks eventually.

If the common reserves are sufficiently small initially, the first phase disappears entirely. The price starts from some level $\alpha^* > p^*$ and grows over time at the rate of interest. Again the phase where stocks are stored above ground is divided into two intervals, one where private

[10] As in all Hotelling models, there is, after this point, a trivial indeterminacy in the price path. Any price path which exceeds the choke price, has no upward jumps, and never rises faster than the rate of interest would constitute an equilibrium. Any such price path induces zero demand, zero extraction, and zero storage. For simplicity, we assume that the price path continues to rise at the rate of interest after the choke price is reached. We make an analogous assumption in the next subsection and assume that the price continues to rise at a rate which would give private extractors no incentive to sell at prices above the choke level.

stockpiles accumulate until the common is drained and the other where market demand must be satisfied entirely by the decumulation of private inventories.

Denote the length of the first phase as θ. Let $H(p,\theta)$ denote the cumulative demand when the price remains at p^* for θ weeks and then grows from p at the rate of interest until demand is choked off:

$$H(p,\theta) = \theta D(p^*) + \int_{u=0}^{\infty} D(pe^{ru})du. \tag{1}$$

Let S_0^{c*} be the initial reserves which would just satisfy cumulative demand at a price path starting at p^* and rising at the rate of interest. That is,

$$S_0^{c*} = H(p^*, 0). \tag{2}$$

Recall that the initial size of the common reserves is denoted S_0^c. We distinguish two cases: $S_0^c \geq S_0^{c*}$ and $S_0^c < S_0^{c*}$.

Case 1

Suppose $S_0^c \geq S_0^{c*}$, and let θ^* denote the equilibrium value of θ. Then

$$\theta^* = \frac{S_0^c - S_0^{c*}}{D(p^*)}. \tag{3}$$

and the equilibrium price path is:

$$p(t) = \begin{cases} p^* & \text{if } 0 \leq t < \theta^* \\ p^* e^{r(t-\theta^*)} & \text{otherwise.} \end{cases} \tag{4}$$

Since, as noted above, extraction exceeds demand as long as reserves remain and $p > p^*$, there exists some $\nu^* > 0$ such

$$\int_{u=0}^{\nu^*} AC^{-1}(p^* e^{ru})du = S_0^c - \theta^* D(p^*) = S_0^{c*}. \tag{5}$$

Extraction from the common is constant until $t = \theta^*$ and then strictly increases until the common reserves are exhausted ν^* weeks later; at that point, extraction jumps discontinuously to zero. That is,

$$x^c(t) = \begin{cases} AC^{-1}(p^*) = D(p^*) & \text{if } 0 \le t \le \theta^* \\ AC^{-1}(p(t)) > D(p(t)) & \text{if } \theta^* < t \le \theta^* + \nu^* \\ 0 & \text{otherwise.} \end{cases}$$

The equilibrium is depicted in the three panels of Figure 1. Panel (a) depicts the upward-sloping average cost function, the downward-sloping demand function, and the vertical component of their point of intersection, p^*. Panel (b) depicts the equilibrium price path as a continuous function of time. Panel (c) depicts the paths of extraction and demand. When the former exceeds (respectively, falls short of) the latter, the difference goes into (respectively, comes out of) private stockpiles.

[Figure 1 Goes Here]

Case 2

If the initial reserves on the common are sufficiently small ($S_0^c < S_0^{c*}$) then the second phase commences immediately. Let $\alpha^* > p^*$ be the initial price on a path rising at the rate of interest and inducing a cumulative demand of S_0^c. That is, α^* is implicitly defined by the following equation:

$$S_0^c = H(\alpha^*, 0). \tag{6}$$

The price at any time $t \geq 0$ is simply $p(t) = \alpha^* e^{rt}$. Since extraction strictly exceeds demand as long as the common contains unexploited reserves, the length of time during which extraction occurs and private stocks accumulate (ν^*) is defined by

$$\int_{u=0}^{\nu^*} AC^{-1}(\alpha^* e^{ru}) du = S_0^c, \tag{7}$$

an obvious specialization of (5).

The price path which results when there are *multiple* common properties with different costs of extraction is qualitatively similar. It is continuous and consists of horizontal segments at different heights, each linked by phases where the price rises at the rate of interest. The price must be constant when no storage occurs since neither the demand curve nor the average cost curve of any pool with strictly positive reserves changes over time. The level of this constant price depends on the horizontal sum of the average cost curves of those pools with positive reserves. When storage does occur, the price must rise by the rate of interest from one plateau to the next to induce the holding of inventories.[11]

2.2 Private Underground Reserves as Well as Common Property

When, in addition to common property, there exist private underground reserves, the equilibrium is more complicated. Unlike the agent extracting from the common pool, it is in the interest of an owner of private reserves to take account of the fact that when he extracts a unit of the resource today he foregoes the opportunity of extracting it tomorrow. Hence his full marginal cost at time t is composed of the marginal cost of extraction as such, which we will assume constant and denote k, plus the shadow value of leaving the resource in the ground for future extraction, which we denote $e^{rt}\mu$. Since the instantaneous profit from extraction from the underground stock does not depend on the remaining stock, the discounted shadow value, μ, is a constant. For any given level of reserves in the common pool, μ is a monotone decreasing function of the initial level of the private reserves, tending to zero as they tend to infinity.

It is useful to distinguish two regimes: $p^* \leq k + \mu$ and $p^* > k + \mu$. In the former

[11] In cases where the order of exhaustion of the pools is obvious, the price path is easily constructed. One example where the order of exhaustion is clear is when each pool has a different but constant average cost. In that case the pools would be exhausted in order of their costs with the lowest cost pool exhausted first. Another example would be where the average cost curves are upward-sloping but do not intersect and where the pool with the larger supply at any price has the smaller reserves. In that case, the pools would be depleted in order of their size with the smallest pool depleted first.

regime ($p^* \leq k + \mu$), we will see that the extraction of private underground reserves does not commence until the common is entirely drained and all aboveground storage ceases as well. This must occur if $p^* \leq k$ and may occur even if $p^* > k$. The equilibrium price path resembles the paths discussed in the previous subsection but with a final phase tacked on at the end during which all of the extraction of private underground reserves occurs. We use the same symbol to denote a variable corresponding to the previous situation without private reserves but add a circumflex to distinguish the situation with private as well as common reserves. Whether the price path has a horizontal segment lasting $\hat{\theta}^*$ weeks at p^* or instead begins at $\hat{\alpha}^* > p^*$ and rises from the outset to compensate holders of aboveground stocks depends on the sizes of the initial reserves. But in either case, aboveground storage ceases before the choke price is reached and a final phase then commences during which all the extraction of private underground reserves occurs.

In the latter regime ($p^* > k + \mu$), some private extraction of underground reserves must occur in a preliminary phase *before* the price rises to p^*. Either all the private extraction can occur in this preliminary phase or, alternatively, some can occur in an initial phase and the rest in a later phase which begins only after the decumulation of the stored reserves taken from the common property. If private extraction occurs at prices below p^*, the price must rise at a rate sufficient to make the private extractors indifferent when they sell. As the price increases, the excess of demand over extraction from the common declines to zero. Private extraction, which covers the deficit, must decline to zero as p^* is reached.

Note that in either case, it can never be optimal for the owner of a private underground stock to be extracting while private storage from the common pool is in progress. For if price is growing at a rate which makes profitable the storage of inventories above ground, it also makes profitable the withholding of extraction of underground reserves.

The determination of the lengths of each phase depends on the two initial reserves. Let $S(t)$ denote the remaining private reserves at date t and S_0 denote the initial private reserves. Let τ denote the date at which private storage of the common resource begin Define $l(p, S(\tau))$ as the solution to:

$$\int_{u=0}^{\infty} D\left((pe^{rl} - k)e^{ru} + k\right) du = S(\tau).$$

That is, l is the length of time a price would have to rise in the storage phase at the rate o interest, from initial level p, so that if the price subsequently rose at the slower rate required to make the private extractors indifferent, this final phase of the price path would induce a cumulative demand equal to the private reserves left under ground at the date storage begins. Note that $l(p, S(\tau))$ is well defined only for $S(\tau) > 0$.

Let $\hat{H}(p, \hat{\theta}, l(p, S(\tau)))$ denote that portion of cumulative demand induced when the price remains at p^* for $\hat{\theta}$ weeks and then grows from p at the rate of interest for $l(p, S(\tau))$ weeks:

$$\hat{H}(p, \hat{\theta}, l(p, S(\tau))) = \hat{\theta} D(p^*) + \int_{u=0}^{l(p,S(\tau))} D(pe^{ru}) du. \tag{8}$$

Clearly, when $p^* \leq k + \mu$, no extraction from the private reserves will have occurred when private storage from the common resource begins and so $\tau = \hat{\theta}$ and $S(\tau) = S_0$.

Finally, let $\hat{S}_0^{c*}$ be the common reserves demanded cumulatively along a price path starting at p^* and rising immediately from p^* at the rate of interest for $l(p^*, S(\tau))$ weeks. That is,

$$\hat{S}_0^{c*} = \hat{H}\left(p^*, 0, l(p^*, S(\tau))\right). \tag{9}$$

We now consider successively the two regimes described above.

Regime 1

If $p^* \leq k+\mu$, we may, as in the situation with no private underground reserves, distinguish two cases, depending on whether $S_0^c \geq \hat{S}_0^{c*}$ or $S_0^c < \hat{S}_0^{c*}$.

Whenever $S_0^c \geq \hat{S}_0^{c*}$, then

$$\hat{\theta}^* = \frac{S_0^c - \hat{S}_0^{c*}}{D(p^*)}$$

and the equilibrium price path is:

$$p(t) = \begin{cases} p^* & \text{if } 0 \leq t < \hat{\theta}^* \\ p^* e^{r(t-\hat{\theta}^*)} & \text{if } \hat{\theta}^* \leq t < \hat{\theta}^* + l(p^*, S_0) \\ (p^* e^{rl(p^*,\, S_0)} - k)e^{r(t-\hat{\theta}^*-l(p^*,\, S_0))} + k & \text{otherwise .} \end{cases} \tag{10}$$

If, on the other hand, the initial reserves in the common are sufficiently small ($S_0^c < \hat{S}_0^{c*}$), the storage phase commences immediately. Define the initial price ($\hat{\alpha}^*$) as follows:

$$S_0^c = \hat{H}\left(\hat{\alpha}^*, 0, l(\hat{\alpha}^*, S_0)\right). \tag{11}$$

Then the equilibrium price path is:

$$p(t) = \begin{cases} \hat{\alpha}^* e^{rt} & \text{if } 0 \leq t < l(\hat{\alpha}^*,\ S_0) \\ (\hat{\alpha}^* e^{rl(\hat{\alpha}^*, S_0)} - k)e^{r(t-l(\hat{\alpha}^*, S_0))} + k & \text{otherwise .} \end{cases} \tag{12}$$

Regime 2

If $p^* > k + \mu$, then price path is more complex than in regime 1. We will now have

$$\hat{\theta}^* < \frac{S_0^c - \hat{S}_0^{c*}}{D(p^*)} \text{ and } \tau^* > \hat{\theta}^*$$

and the equilibrium price path will be:

$$p(t) = \begin{cases} (p^* - k)e^{r(t-(\tau^*-\hat{\theta}^*))} + k & \text{if } 0 \le t < \tau^* - \hat{\theta}^* \\ p^* & \text{if } \tau^* - \hat{\theta}^* \le t < \tau^* \\ p^* e^{r(t-\tau^*)} & \text{if } \tau^* \le t < \tau^* + l(p^*, S(\tau^*)) \\ (p^* e^{rl(p^*,S(\tau^*))} - k)e^{r(t-\tau^*-l(p^*,S(\tau^*)))} + k & \text{otherwise .} \end{cases} \tag{13}$$

Some exceptional price path configurations may arise in this regime. For instance, it is conceivable that the private reserves are completely drawn down ($S(\tau) = 0$) as the price path reaches p^*. The rest of the path is then exactly what we described in the absence of private underground reserves, for the case of sufficiently large initial common reserves. Formally, the interval $l(p^*, 0)$ is not defined nor is the last phase. From τ^* on, the price path therefore follows $p(t) = p^* e^{r(t-\tau^*)}$. Alternatively, the initial private reserves may be so large as to completely dominate the determination of the price path, resulting in the disappearance of the two middle stages and an equilibrium price path given by $p(t) = (p^* - k)e^{rt} + k$. Such a path induces private extraction throughout and common property extraction only if the price is below p^*. Hence, the second phase of private extraction follows the first with no intermediate phase of storage. As price rises to some $\tilde{p} \le p^*$, the commons is exhausted and private extraction jumps up by $AC^{-1}(\tilde{p})$ to replace it.[12] Formally, $\theta^* = 0$, from which it follows that necessarily $l(\tilde{p}, S(\tau^*)) = 0$. Notice that whereas in regime 1 above, $\theta^* = 0$

[12]The scenario described in the text relies heavily on the assumption that the marginal cost of extraction is constant. Denote the total cost of private extraction by $k(\cdot)$. As long as the marginal cost of satisfying the full demand from private reserves is any larger than the marginal cost of extracting zero ($k'(D(p^*)) > k'(0)$), *some* reserves extracted from the commons *must* be stored. For suppose not. Then at the moment when the common property is drained and its rate of exploitation jumps from $AC^{-1}(\tilde{p}) > 0$ to zero, the rate of private extraction must—in the absence of any storage—jump in the opposite direction by the same amount. But given our assumption about the marginal cost curve of the private extractor, his marginal profit in the instant before these offsetting jumps would be *strictly* larger than his marginal profit in the instant after them: the price would be $\tilde{p}$ in either case but the upward jump in extraction would, by hypothesis, induce some increase in the marginal cost. But since the marginal profit after the jumps is smaller, the private extractor would alter his behavior—extracting less after the jump and more before it than we hypothesized. But what we hypothesized was *necessary* if supply is to equal demand in the absence of storage. The conclusion is inescapable: storage of reserves extracted from the commons *must* occur in the equilibrium as long as $k'(D(\tilde{p})) > k'(0)$.

could only occur for $S_0^c = \hat{S}_0^{c*}$, it now occurs only when common reserves are completely drawn down as $\tilde{p}$ is reached. This explains why $l(\tilde{p}, S(\tau^*))$ must vanish, since there can be no storage phase if there are no reserves left in the common pool.[13]

It is interesting to consider the situation where the private and the common pool can each be extracted at *constant* marginal cost. We continue to denote the constant marginal cost of extracting from the private property as k; the constant marginal cost of extracting from the common property is simply p^* since the horizontal average cost curve will intersect the demand curve at that point. Two possibilities are of interest: $p^* = k$ and $p^* > k$.

If $p^* = k$, the analysis of regime 1 applies: the common reservoir must be exhausted and the aboveground stocks from it depleted before extraction of the private pool commences. This contrasts with the standard situation of two privately owned pools which can be extracted at identical marginal costs: there would then be an indeterminacy in the competitive equilibrium as to the source of the aggregate output in a given period. If $p^* > k$ then, as we have seen, it is possible in a competitive equilibrium for the common property to be entirely drained before extraction from the private property commences. This occurs whenever $p^* < k + \mu$. This order of extraction contrasts with the standard result of Herfindahl (1967) that, when both pools are privately owned, the pool which is cheaper to extract must be exhausted before the extraction begins on the higher cost pool.

2.3 Naturally Occurring Speculative Attacks

Whether or not there are private reserves, if the initial reserves of common property are sufficiently large, extraction from them will occur at a uniform rate for an interval of time. Then extraction increases for ν^* more weeks as the price rises from p^* at the rate of interest and stocks accumulate at an increasing rate above ground. Accumulation stops only when the

[13]The demonstration is straightforward that, for any pair of initial reserves (one private and the other common), a unique competitive equilibrium price path exists. We omit this proof to conserve journal space but will make it available upon request.

common is completely drained of reserves, at which point decumulation of the private stockpiles begins. When these are completely drawn down, consumption either ceases altogether or is satisfied entirely by private extraction depending on the situation under consideration.

Notice a striking characteristic of these equilibria. The length of the interval during which private inventories are accumulated in either situation (ν^*) depends on the slope of the average cost curve. If that curve is horizontal, the accumulation is *instantaneous* ($\nu^* = 0$.). This means that after declining at the finite rate $D(p^*)$, the remainder of the common property is suddenly depleted at an *infinite rate* in one frenzied instant and then stored privately. If instead the average cost curve has a small positive slope, the frenzied drainage of the common and accumulation of private stocks requires a short time interval. In cases where the initial price exceeds p^* because initial common reserves are sufficiently small, the frenzied accumulation begins immediately.

This precipitous behavior is a manifestation of what Salant and Henderson (1978) first identified as a "speculative attack" in connection with their analysis of the run on the government stockpiles of gold used to defend the official price ceiling of $35 per ounce. A striking difference, however, is that here the speculative attack occurs in the *absence* of any government policy: it is naturally-occurring.[14]

In the more realistic situation where there is *uncertainty* about the size of the reserves in the common, *multiple* speculative attacks should occur in the absence of any government intervention.[15] Consider the case of a common property which can be extracted at constant average (equals marginal) cost p^*. Suppose each potential stockpiler believes that the reserve level is R_i with probability π_i for $i = 1, \ldots, n$.[16] As a convenience, let $R_0 = 0$. Define the

[14] In the case of multiple pools of common property discussed at the end of subsection 2.1, if the average cost of extraction at each pool is constant, then each storage phase commences with an attack: there are *multiple* speculative attacks, but never on the same pool.

[15] The case analyzed below can easily be translated into the context of international finance. There the common is replaced by a government committed to selling whatever reserves are necessary to place a ceiling on its exchange rate and speculators are uncertain about the size of the government's reserves.

[16] For the corresponding analysis of socially optimal extraction with unknown reserves (in the *absence* of aboveground storage), see Gilbert (1979).

increment between reserve levels as $\Delta_i = R_i - R_{i-1}$ for $i = 1, \ldots, n$. Denote the probability that initial reserves are exactly R_i, *conditional* on their being *at least* R_i, as

$$\hat{\pi}_i = \frac{\pi_i}{\sum_{j=i}^{n} \pi_j} \text{ for } i = 1, \ldots, n.$$

Note that $\hat{\pi}_n = 1$.

Let $P(S, \bar{p})$ be the initial price on a path which rises at the rate of interest until it reaches $\bar{p}$ and induces cumulative demand of S. Let $T(S, \bar{p})$ denote the length of time required for the depletion of the S units of reserves to occur. $P(S, \bar{p})$ has the following properties: (1) continuous in S, (2) strictly decreasing in S, (3) $P(S_0^{c*}, \bar{p}) = p^*$, and (4) $P(S, \bar{p}) \leq \bar{p}$ with equality if and only if $S = 0$.

Define S_i^* as the solution to the following equation:

$$p^* = \hat{\pi}_i P(S_i^*, \bar{p}) + (1 - \hat{\pi}_i) P(S_i^*, p^*) \text{ for } i = 1, \ldots, n.$$

Given the four properties of the $P(\cdot)$ function, this equation uniquely defines $S_i^* \in (0, S_0^{c*})$ for $i = 1, \ldots, n$. It follows that the price will jump above p^* if it turns out that the common is exhausted but will collapse below p^* if there turn out to be more reserves underground. Assume $\Delta_i - S_i^* > 0$ for $i = 1, \ldots, n$.

Let $i = 1$. In the competitive equilibrium, extraction continues for $\Theta_i^* = \frac{\Delta_i - S_i^*}{D(p^*)}$ weeks with the price equal to p^*. At that point, speculators suddenly purchase S_i^*. If the common is exhausted, the price jumps up to $P(S_i^*, \bar{p}) > p^*$ and the inventories acquired are sold off gradually until, $T(S_i^*, \bar{p})$ weeks later, the choke price is reached. The other possibility is that speculators infer that more reserves remain in the common. The price then collapses to $P(S_i^*, p^*) < p^*$ and extraction ceases for $T(S_i^*, p^*)$ weeks until the inventories acquired in the attack are worked off and the price of p^* is regained. At that point, extraction resumes and the entire process evolves in the same way with $i = 2$... This behavior is optimal for the speculators given the sequence of state-contingent prices since they acquire stocks at a price equal to the discounted mean of the prices they expect to obtain when they sell and then liquidate those stocks before the price stops rising, a phase they can perfectly foresee given what they learn immediately after the most recent attack.

Suppose the true state is R_n. Then, immediately after the $n-1^{st}$ attack, reserves remain and everyone infers that there were initially R_n reserves of which Δ_n remain. There is, therefore, no longer any uncertainty about the size of the reserves in the common. This returns us precisely to the certainty case described above. In this event, the previous two equations imply that $\hat{\pi}_n = 1$ and $S_n^* = S_0^{c*}$. The price immediately after the final attack is therefore $P(S_n^*, \bar{p}) = p^*$, as we concluded earlier. In terms of the generalization to uncertainty just summarized, since there is *no downside risk* when the n^{th} attack occurs, there is *no upward price jump* necessary immediately following the attack to compensate the speculators for a potential capital loss.

Government policies can, to be sure, also induce attacks in the context of common properties. We will see a prominent example in Section 4 when we discuss cumulative catch constraints on fisheries.

3 Welfare Comparisons

> When many different landholdings lay over an oil pool, unregulated production soon turned into a pumping contest, with each individual drilling as many wells as possible and running them wide open. This was the practice in Texas for a generation after Spindletop. In every reservoir, it resulted in a huge waste because it guaranteed dissipation of reservoir energy. Once 5 or 10% of the original oil had been produced, the water or gas drive was expended and the wells stopped flowing. Texas is dotted with small towns like Borger that went from boomtown to ghost town in a few years, because the frantic pace of development in their fields used up the pressure in their reservoirs.—Prindle (1981), p. 24

Until now, we have abstracted from an important geological fact: extraction beyond a threshold rate often weakens the gas or water drive propelling oil to the surface, thus reducing ultimate recovery.[17] This threshold rate is referred to in the engineering literature as the "Maximum Efficient Rate of Extraction" or MER.[18] We have not mentioned it before because its existence alters neither the extraction response under free access to any given price nor the qualitative characteristics of the intertemporal equilibrium.[19] The existence of an MER threshold, however, does affect the socially optimal extraction plan. We discuss this plan in the first subsection below and then compare it to equilibrium under free access.

Hotelling (1931) and others derived the socially optimal extraction plan under the assumption that there is no MER threshold. Suppose, however, such a threshold in fact exists. If the extraction program Hotelling derived *never* exceeds the MER threshold, it would still be optimal. If it does sometimes exceed the MER threshold (and the leakage coefficient is nonzero), then leakage would occur and the initial reserves would be insufficien to support the proposed extraction program. We derive the optimal program in such cases and find it sometimes optimal to induce leakage. As we show, however, when the pool is extracted under free access (with or without storage) leakage necessarily exceeds the optimal level. When private storage is possible, ultimate recovery under free access is even smaller.

This raises the question of whether the opportunity to store as private property oil extracted from the common improves welfare or whether, as General Thompson suggested, it is always better to leave the oil in "God's reservoir" until it is needed. We resolve this issue in the final subsection.

3.1 First Best: The Social Optimum When Speed of Extraction Reduces Ultimate Recovery

Let x denote the rate at which a resource is extracted from a reservoir for consumption,

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[17] In the case of fish, a similar phenomenon occurs. Rapid extraction involves huge nets. Immature fish caught in such nets are lost; they never have the opportunity to mature to a point where they would be of economic value.

[18] McFarland (1976) provides a valuable survey of the MER concept in the engineering literature.

[19] It would alter θ^* and ν^* of section 2.1 since initial reserves must now equal the *sum* of cumulative demand and the reserves that are wasted along the proposed equilibrium extraction path.

storage, or other uses. Assume that, if this rate of extraction exceeds a critical threshold (denoted E), some underground reserves are permanently lost—with the rate of loss proportional to the gap between the extraction rate and the threshold. When extraction is sufficiently hasty, underground reserves decline more rapidly than usable resources reach the surface: $\frac{dS}{dt} = -x - \gamma \max\{0, x - E\}$. Denote by $U(\cdot)$ the instantaneous gross benefit function and assume that the social and market rates of interest (r) coincide. Then, in the absence of a storage technology, socially optimal extraction solves the following dynamic optimization problem:

$$\max_{x(t)} \int_0^\infty \left[U(x(t)) - C(x(t))\right] e^{-rt} dt$$

subject to:

$$\frac{dS}{dt} = -x(t) - \gamma \max\{0, x(t) - E\}$$

$$x(t) \geq 0, S(t) \geq 0 \quad \text{and} \quad S(0) = S_0,$$

where $C(x) = xAC(x)$

Let λ be the discounted shadow value of leaving the resource in the ground for future extraction[20]. According to the Maximum Principle, the optimal extraction rate ($x \geq 0$) maximizes $U(x) - C(x) - \lambda e^{rt}(x + \gamma \max\{0, x - E\})$ at each instant. Denote the extraction rate maximizing this function as $x(t, \lambda)$. When the reserve constraint is binding, the multiplier associated with the optimal program (denoted λ^*) solves the following endpoint condition:

$$\int_0^\infty \left[x(t, \lambda^*) + \gamma \max\{0, x(t, \lambda^*) - E\}\right] dt = S_0.$$

The function maximized at each instant (the Hamiltonian) is continuous, strictly concave,

[20]Since $S(t)$ does not appear in the functional to be maximized, λ is a constant.

but kinked at $x = E$. One of the following conditions will hold at each t if the program is socially optimal:

$$x > E > 0 \quad \text{and} \quad U'(x) - C'(x) - \lambda e^{rt}(1+\gamma) = 0, \text{ or}$$
$$x = E \quad \text{and} \quad \gamma\lambda e^{rt} \geq U'(x) - C'(x) - \lambda e^{rt} \geq 0, \text{ or}$$
$$E > x > 0 \quad \text{and} \quad U'(x) - C'(x) - \lambda e^{rt} = 0, \text{ or}$$
$$x = 0 \quad \text{and} \quad U'(0) - C'(0) - \lambda e^{rt} \leq 0.$$

This solution may be visualized with the aid of Figure 2. In the diagram, we plot the downward-sloping schedule of marginal benefits ($U'(x)$) and the upward-sloping schedule of full marginal costs. The latter is discontinuous. For $x < E$, the full marginal cost is $C'(x) + \lambda e^{rt}$. For $x > E$, however, it is $C'(x) + \lambda e^{rt}(1+\gamma)$. The full marginal cost is undefined at $x = E$ since the full total cost function is kinked at that point. Optimal extraction may be read from Figure 2 as the horizontal component of the intersection point of the two curves. There are three cases of interest.

[Figure 2 Goes Here]

If the initial stock is sufficiently small, then at $t = 0$ the two curves intersect to the left of E. The smallest multiplier inducing initial extraction of E is $\tilde{\lambda} = U'(E) - C'(E)$. Hence, the largest initial stock inducing this outcome is $\tilde{S}_0$, the implicit solution to the following equation: $\int_0^\infty x(t, \tilde{\lambda})dt = \tilde{S}_0$. For any initial stock $S_0 \in [0, \tilde{S}_0)$, extraction commences with $x(0) \in [0, E)$. Over time, the upward-sloping full marginal-cost curve shifts up and the intersection point of the two curves moves leftward — implying that optimal extraction declines monotonically to zero.

At the other extreme, if the initial stock is sufficiently large, then extraction commences with $x(0) > E$. In that case, extraction declines monotonically to E, lingers there for an interval of d years, and then declines to zero. The largest multiplier inducing initial extraction of E is $\bar{\lambda} = (U'(E)-C'(E))/(1+\gamma)$. Hence, the smallest initial stock inducing this outcome is $\bar{S}_0$, the implicit solution to the following equation: $\int_0^\infty \left[x(t,\bar{\lambda}) + \gamma \max\{0, x(t,\bar{\lambda}) - E\}\right] dt = \bar{S}_0$. For any initial stock $S_0 \in (\bar{S}_0, \infty)$ extraction commences with $x(0) \in (E, \infty)$.

For initial stocks of intermediate size ($S_0 \in [\tilde{S}_0, \bar{S}_0]$), extraction commences with $x(0) = E$. The full marginal cost associated with larger extraction would strictly exceed the resulting marginal benefit while the full marginal cost of smaller extraction falls short of the marginal benefit. In this situation, extraction remains at E for that interval of time during which the point of intersection of the curves in Figure 2 occurs on the vertical segment of the full marginal-cost curve; thereafter, extraction declines monotonically to zero.

Suppose the initial stock is sufficiently large that extracting faster than the MER at the outset is socially optimal. Then, the marginal benefit of the resource *net* of the cost of extraction grows at the rate of interest during the initial phase, remains constant for d years,[21] and resumes its growth at the rate of interest during the final phase. The optimality of this path merits some discussion. Since the net price rises by the rate of interest as long as the rate of extraction exceeds the MER, marginal perturbations *within* this phase cannot strictly increase social surplus. Reducing extraction early in the final phase makes an expansion of the same magnitude feasible later in the phase. Since the net gain and net loss have the same discounted value, such a perturbation will not alter discounted social surplus. For similar reasons, marginal perturbations *within* the last phase cannot strictly increase discounted social surplus. However, it may *seem* initially as if social surplus could be strictly increased by expanding extraction in the first phase and reducing it by an equal amount in the last phase since the discounted net marginal utility in the final phase is *strictly smaller* (by the factor $1/(1+\gamma)$) than in the initial phase. Such an arbitrage is infeasible, however. A one barrel reduction in extraction in the last phase does *not* permit an expansion

[21] It is straightforward to define d analytically. Note that if the initial stock is $\bar{S}_0$, extraction remains at E for the full d years. Since $C'(E) + \bar{\lambda}(1+\gamma) = U'(E)$ at the outset while $C'(E) + \bar{\lambda}e^{rd} = U'(E)$ at the last instant of this phase, $d = \frac{1}{r}\ln(1+\gamma)$.

of extraction in the first phase of an equal amount. It permits an expansion then of a mere $1/(1+\gamma)$ barrels — the remaining $\gamma/(1+\gamma)$ barrels would be trapped underground as a consequence of expanding extraction which already exceeds the MER. Hence even though extracting one barrel less in the last phase sacrifices in discounted terms only $1/(1+\gamma)$ of the net utility which would be gained if one barrel *were* extracted in the first phase, in fact the gain in the first phase would be only $1/(1+\gamma)$ as large since only that fraction of an additional barrel could be extracted. As a result, there would be no gain from the proposed arbitrage and none if that arbitrage were reversed.

Note that in all of these cases, the marginal benefit associated with optimal extraction $(U'(x))$ rises by less than the rate of interest. It follows that there is no incentive for the planner to store oil above ground even if it could be done costlessly. Consequently, the extraction path described above is optimal even if the resource may be stored.[22]

3.2 Free Access Equilibrium When Speed of Extraction Reduces Ultimate Recovery

We now examine how the same reservoir would be exploited under free access. Consider first the case where storage is infeasible. Graphically, extraction at each point in time can be read from the diagram in Figure 2 as the horizontal component of the point of intersection of the downward-sloping demand curve $(U'(x))$ and the upward-sloping *average* cost curve. Note that neither of these two curves shifts over time. Moreover, since the average cost curve lies uniformly below the marginal cost curve, it lies uniformly below the full marginal-cost curve. This implies that extraction under free access in the no storage case is initially faster than is socially optimal. Moreover, the rate of extraction remains constant in the

[22]When the economically efficient plan involves leakage, a petroleum engineer would criticize it as "technically inefficient." This is an unusual situation since in most familiar cases, economic efficiency *presupposes* technical efficiency. The case at hand is reminiscent of the debate between economists and biologists over the optimality of the maximum sustainable yield. In each case, the economist takes account of the costs of postponing consumption and the noneconomist disregards this consideration.

free-access case while socially optimal extraction weakly declines over time. This implies that extraction under free access exceeds socially optimal extraction as long as there remain reserves to exploit. Extraction would therefore terminate sooner in the free-access case. If faster extraction, in addition, reduces ultimate recovery, this would be an independent force causing extraction in a free-access equilibrium to terminate sooner than socially efficient extraction. Moreover, under free access, ultimate recovery would be suboptimal as well.

Suppose instead that the resource could be privately stored above ground at zero cost. As we have see, there are two cases to distinguish. In the first, equilibrium extraction remains at $AC^{-1}(p^*)$ for an interval of time and then strictly increases until reserves are depleted; in the second, equilibrium extraction begins at the faster rate $AC^{-1}(\alpha^*)$ and then strictly increases until reserves are exhausted. Hence, in both cases, equilibrium extraction under free access begins faster than socially optimal extraction and weakly increases over time until reserves are exhausted whereas socially optimal extraction weakly declines from its initially lower level. Because extraction under free access is uniformly faster with storage than without it, extraction would cease sooner. If faster extraction reduces ultimate recovery, this would be an independent force causing extraction under free access to terminate sooner and with less ultimately recovered when storage is feasible. Let T denote the time when extraction ceases and R denote the reserves ultimately recovered. Let the first subscripts fa and p refer to the free access case and the social planner case, respectively; let the second subscripts s and ns refer to storage and no storage, respectively. Then we may summarize our conclusions as follows: $T_{fa,s} < T_{fa,ns} < T_{p,s} = T_{p,ns}$ and $R_{fa,s} < R_{fa,ns} < R_{p,s} = R_{p,ns}$. The three panels of Figure 3 summarize other aspects of the comparison between the social optimum on the one hand and extraction under free access (with or without storage) on the other.

[Figure 3 Goes Here]

3.3 Is the Ability to Store Common Reserves as Private Stockpiles Socially Beneficial?

The following question naturally arises: does welfare necessarily increase because of the availability of a storage technology combined with a legal regime which treats extracted common property as private property? It is to this normative issue which we now turn.

There are two conflicting considerations. On the one hand, the social cost of transferring common reserves to private storage may be high. On the other hand, once the transfer is accomplished and the stocks are privately held, they will be allocated efficiently. As we will see, either of these two effects can dominate. To examine these two effects in the starkest setting, we omit considerations of the MER until the end.

To isolate the beneficial effect of storage, consider the extreme case where extraction is *costless*. As a benchmark, consider first the extraction path which maximizes discounted surplus. Since extraction cost is assumed to be zero, the marginal benefit must rise by the rate of interest from a level which induces cumulative demand equal to the initial stock.

Next, consider the extraction path which occurs if the initial reserves are instead common property. Since the average cost curve is horizontal (at zero), the accumulation phase will be instantaneous. Provided the initial stock is sufficiently small ($S_0^c \leq S_0^{c*}$), the speculative attack would occur at the outset and the allocation to consumers over time would coincide with the socially efficient allocation. Since, in the case posited, privatization of the common property *via* storage is costless, this equilibrium is socially efficient.

Strictly *lower* discounted surplus would result in this example if the ability to store above ground were eliminated. For, extraction would proceed at the faster rate $D(0)$ until reserves were exhausted and would then cease altogether. This feast-or-famine intertemporal allocation is suboptimal (Hotelling (1931)). Hence, the availability of a technology permitting the costless transfer of the common reserve to aboveground stockpiles combined with their subsequent legal protection as "private property" is beneficial. It would rectify the inefficiency and would result in the first-best allocation.

This method of privatization, however, is not always so benign. To see why the availability of the storage technology may also *lower* welfare, consider another extreme case — where the demand curve is rectangular and extraction is costly. It is then socially efficient to deplete the underground reserves at a uniform rate until they are exhausted. This is precisely the equilibrium allocation which would occur in the *absence* of any storage technology. The rate of extraction and the market price are, respectively, the horizontal and vertical components of the point where the rectangular demand curve and the horizontal average cost curve intersect. Hence, common property extraction in the absence of any storage technology is socially optimal.

If extraction from the common entails a positive cost, the availability of a storage technology can only lower welfare. Suppose the average cost is constant and reserves are sufficiently low that a speculative attack occurs in the first instant. Then, the consumers would receive the socially efficient allocation over time but the cost of providing it would be unduly high because the transfer of the common reserves to the private stockpiles is expensive. If rapid extraction reduced ultimate recovery, the availability of the storage technology would be even more harmful.

4 Induced Speculative Attacks

> The plan for cod, haddock, and yellowtail was initiated in 1977 and established a total quota for each of the stocks of fish. Fishing licenses were required, but they were easily available and there was no moratorium on entry as there was in the surf clam and ocean quahog fishery. It was soon discovered that with the existing fleet and the many new entrants, the annual quota would be harvested very early in the year. This infuriated fishermen. In the following year the quota was caught early in the year [again]—Anderson (1982), p. 174

> Massachusetts placed a ceiling on the aggregate catch of stripers [striped bass] by commercial fishers. Unfortunately, this is a very poor way to control fishing,

because it encourages each fishing boat to catch as much as it can early in the season before other boats bring in enough to reach the aggregate quota that applies to all of them. This is precisely what happened last year...—Gary Becker (1995)

While our analysis has so far been confined to exhaustible resources, it also has implications for renewable resources as well as goods which can be produced indefinitely. To illustrate, we consider a policy which limits the cumulative amount which can be produced or extracted. Policies of this kind have been used repeatedly to regulate fisheries and have induced surprising responses from the private sector.

Suppose as an initial simplification that the common's reserves are infinite so that the equilibrium price would remain p^* forever. Suppose now the government imposes a limit on cumulative extraction per year (denoted $\bar{Q}$). Suppose the cumulative catch in the original equilibrium exceeds the proposed limit. Then the cumulative restriction imposed by the government substitutes for the cumulative restriction which nature imposes on a resource of finite size and the equilibrium has precisely the characteristics described in section 2. That is, in the new equilibrium, the price will remain constant for θ^* weeks during which extraction will occur at the uniform rate, $D(p^*)$. Then private storage of the common property begins, ceasing ν^* weeks later when everything which is allowed has been extracted and the cumulative catch limit imposed by the government is filled. If the average cost of extraction is horizontal, $\nu^* \to 0$ and, after the delay of θ^* weeks, the remainder of the catch limit is filled in "the twinkling of an eye." Alternatively, if the average cost curve is upward sloping, the remainder of the catch limit is filled during a frenzied interval of $\nu^* > 0$ weeks. The two panels of Figure 4 illustrate a speculative attack induced by a cumulative catch limit:

[Figure 4 Goes Here]

Note that in this reinterpretation of our results from section 2, what is "drained" after ν weeks in the accumulation phase of storage is not the reserves remaining in the commons but instead the *slack remaining* in the cumulative catch constraint.

The government policy which triggers this attack bears no resemblance to the bufferstock policies studied in the literature on speculative attacks. What is identical is the precipitous behavior these policies induce. The evidence is abundant that policies of this kind have the effects predicted.

To conclude this discussion of induced attacks, our simplifying assumption of an infinite stock can now be relaxed. Precisely the same phenomenon can occur if the initial reserves, rather than being infinite, are instead finite but growing rapidly enough that, in the absence of the government total catch limit, reserves exist to satisfy indefinitely the demand at the constant price p^*. The imposition of the cumulative catch limit would then have the effects described above and depicted in Figure 4. Instead of the resource being extracted at a uniform rate indefinitely, after θ^* weeks the remainder of the catch is suddenly filled (or filled after a short additional interval of ν^* weeks).

Given the foregoing observations, we can ask whether the policy of a seasonal catch limit is necessarily welfare improving. It is straightforward to construct an example where the policy is harmful. Reconsider the case where the average cost curve is strictly positive but horizontal and the demand curve is rectangular. Assume the stock is either infinite or at least sufficient to permit continual extraction at the rate $D(p^*)$. Then in the absence of a catch limit, the common property would be extracted continually at the socially optimal rate—a first-best outcome. However, a catch limit will trigger a speculative attack: usage will be unchanged (although consumers will no longer receive fresh fish throughout the year but instead frozen fish after the induced attack). But welfare will be lower since fishing costs would be incurred long before the fish were to be eaten. Catch limits may, therefore, harm social welfare. Since storage may in fact be costly (fish, unlike oil, must be refrigerated) and the frenzied extraction the policy induces may have long-run adverse effects on the fish population, the harm to social welfare from the policy may be even greater.

5 Conclusion

In many cases, storage is a way of transforming common to private property. Other things equal, the opportunity to store results in faster depletion. The accelerating accumulation that occurs when the common is drained for aboveground storage is interpretable in limiting cases as a speculative attack on the common reserves. Whereas the speculative attacks previously studied in the literature are responses to particular government policies, with a storable common property resource these attacks can occur naturally, without government intervention.

When storage is possible, the presence of common property affects the order in which resource pools are exploited. When two private pools have the same constant marginal cost of extraction, the order of their extraction is indeterminate. When one of them is common property, however, it will be exhausted before extraction from the privately-owned pool even begins. In fact, extraction from the private pool may be delayed until after the common pool is fully drawn down even when the private pool is cheaper to extract.

Finally, from a normative point of view, the beneficial effects of privatization may be offset by the social costs of transforming the commons into legally sanctioned private stockpiles. This can occur even if we neglect the possibility that an increased speed of extraction reduces ultimate recovery.

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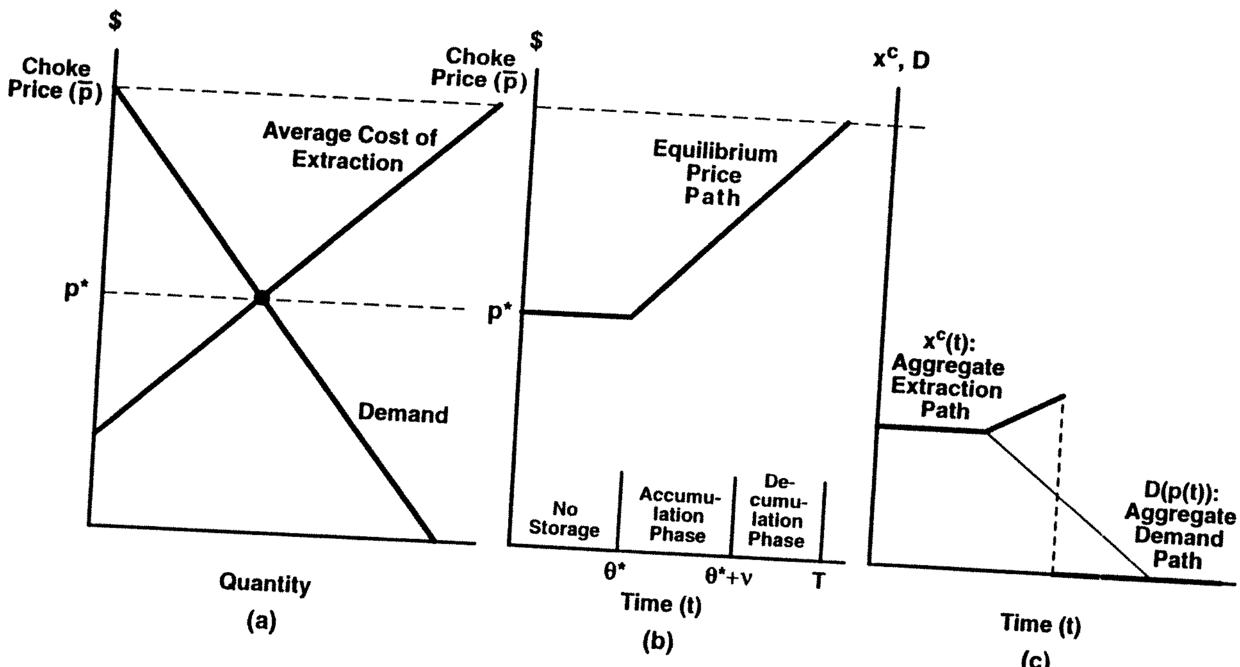


$
Choke Price ($\bar{p}$)
p*
Average Cost of Extraction
Demand
Quantity
(a)
$
Choke Price ($\bar{p}$)
p*
Equilibrium Price Path
No Storage
Accumulation Phase
Decumulation Phase
θ*
θ*+ν
T
Time (t)
(b)
x^c, D
$x^c(t)$: Aggregate Extraction Path
D(p(t)): Aggregate Demand Path
Time (t)
(c)

Figure 1

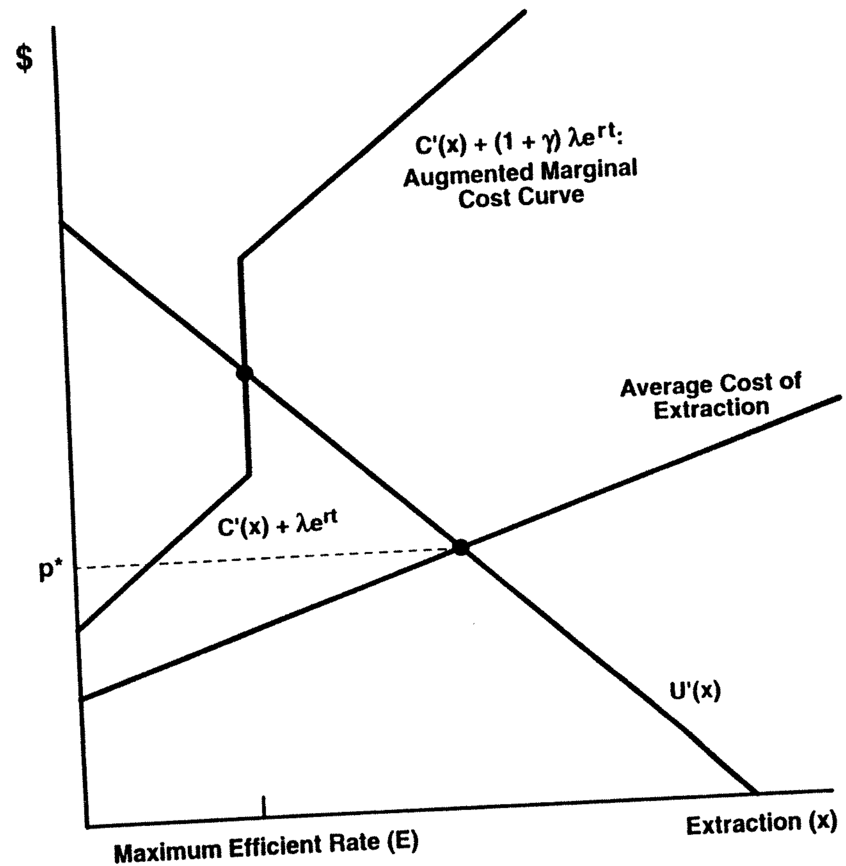

$
C'(x) + (1 + γ) λe^rt:
Augmented Marginal Cost Curve
Average Cost of Extraction
C'(x) + λe^rt
p*
U'(x)
Maximum Efficient Rate (E)
Extraction (x)

Figure 2

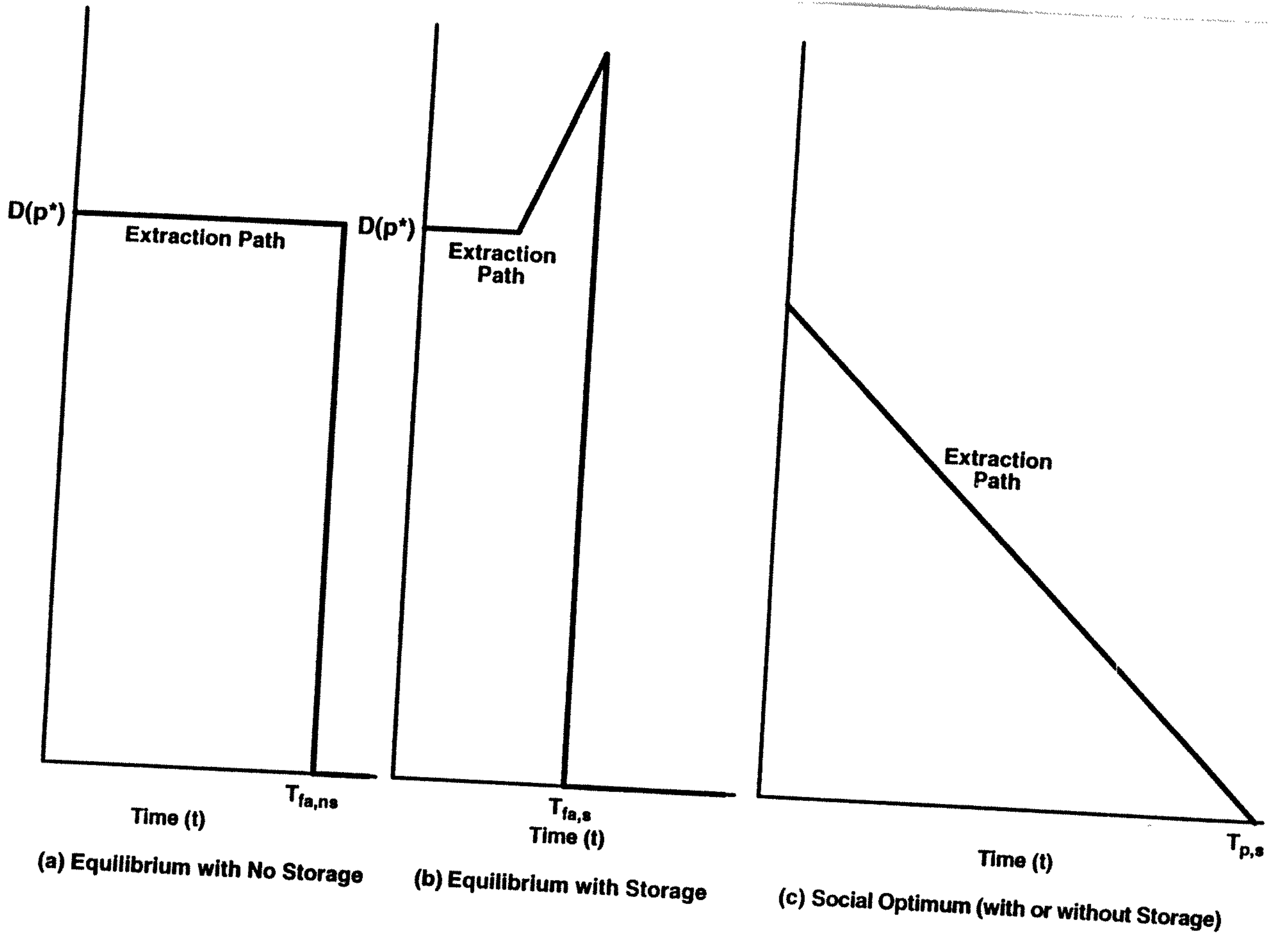
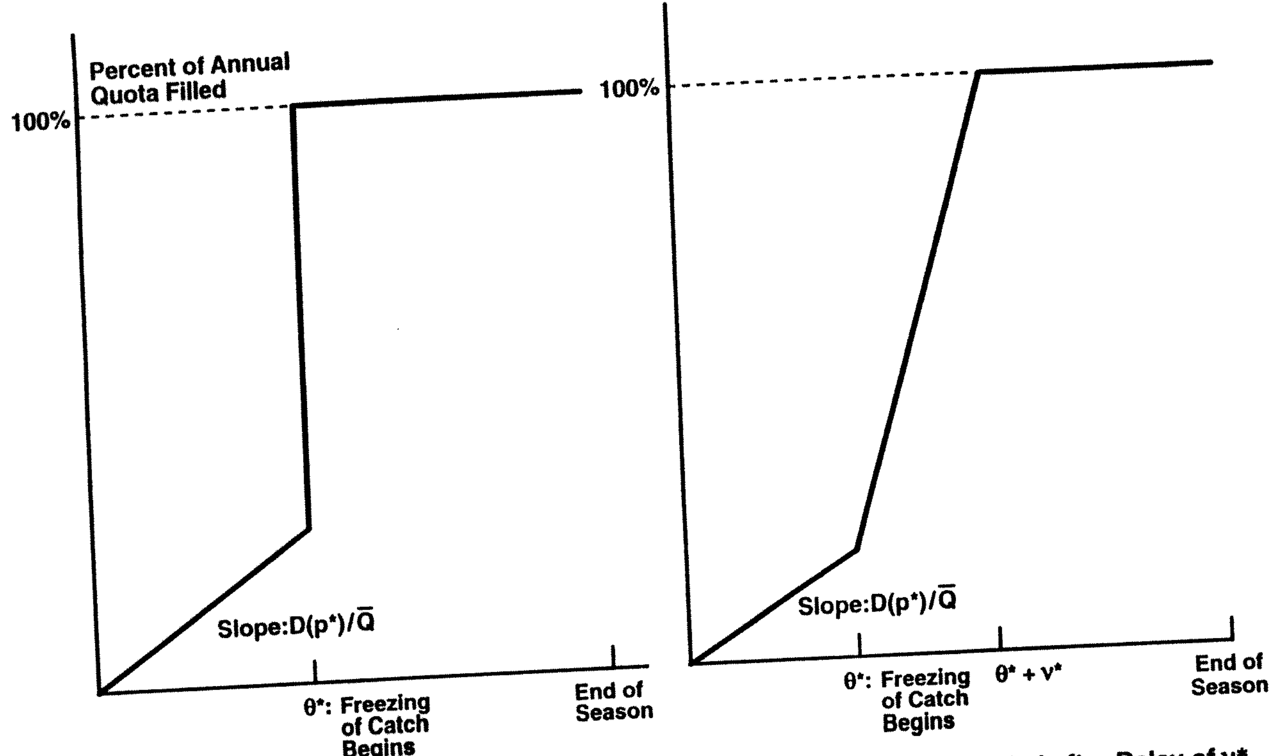

D(p*)
Extraction Path
$T_{fa,ns}$
Time (t)
(a) Equilibrium with No Storage
D(p*)
Extraction Path
$T_{fa,s}$
Time (t)
(b) Equilibrium with Storage
Extraction Path
Time (t)
$T_{p,s}$
(c) Social Optimum (with or without Storage)

Figure 3



(a) Remainder of Quota Filled Instantaneously when $t = \theta^*$

(b) Remainder of Quota Filled after Delay of ν^* beyond $t = \theta^*$

Figure 4

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