



The Mineral Economy: How Prices and Costs Can Falsely Signal Decreasing Scarcity

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Abstract

Natural Resource prices and costs of extraction have declined simultaneously with increasing quantities of extraction for a long time. In a Hotelling sense this indicates decreasing scarcity since low cost resources normally would be used first and quantities of extraction normally would decrease over time. The main reason for the trend being opposite to Hotelling characteristics is usually thought to be due to technological innovation. However, an alternative reason for decreasing costs and prices and increasing quantities of extraction may be due to Georgescu-Roegan's (1972) concept of "Bonanza" where there is only the appearance of decreasing scarcity. Norgaard's (1990) "Mayflower" problem can be used to model an alternative neo-classical approach to resource extraction and scarcity. In this paper, a model of resource exploration is developed where the explorer does not know total reserves of the resource base as he searches for and extracts the natural resource. The explorer never entirely knows how big the resource base is but does gain information about the potential location of new reserves as discovery proceeds. That reduces exploration costs. The lower exploration costs can cause the price to fall over time, until eventually scarcity of the resource causes the price to rise. The true scarcity is only revealed towards the end of exhaustion. The model shows that it is possible to have several years of increasing production simultaneous with lower prices and costs until a sudden, intense price rise occurs with a huge cut in production. When technology is able to cut costs and increase the reserve base, the decline in prices and costs and the increase in production can last longer. However even with better technology, it is still possible for a sharp increase in price as long as demand is growing faster than technological innovation. The problem is that the true size of the resource base is never known. Society does not know if technology is actually overcoming scarcity or not until demand for a resource outstrips supplies. It is even possible for a price shock of incredible magnitude to surprise an economy within one or two years after a hundred years of declining prices and increasing production.

KEYWORDS: Resources, Scarcity, Technology, Exploration, Information, Hubbert, Norgaard's Mayflower problem

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Introduction

According to Hotelling (1931) there are 3 things, we can say about resource extraction for a finite resource. 1) Firms will always try to extract low cost resources before high cost resources causing resource extraction costs to increase over time. 2) In general, greater scarcity caused of in-situ reserves increases the value of a resource causing the price to increase over time. 3) Since the price of a resource increases over time, then demand and production should decrease over time. Barnett and Morse (1964), and more lately Scott and Pearse (1992) and Simon (1996), show that all of these theoretical trends have not occurred. Costs of extraction and prices of natural resources have mostly decreased over time, not just in recent years but in many cases for decades. Quantities extracted and produced of most natural resources have also increased over the same long time frame. The only logical explanation is that technology and substitutes are in fact more powerful than scarcity.

In this paper is shown an alternative model for scarcity based on Norgaard's (1990) Mayflower problem that shows how it is possible for there to appear to be long trends of decreasing scarcity only to have a sudden and dramatic increase in scarcity. The model here shows that long run resource exploration cost, and resource price declines simultaneous with increasing resource extraction, do not necessarily signify decreasing scarcity. The paper shows that the true power of technology in over coming scarcity may be difficult to determine. It is also shown how price and cost measures of scarcity may fail even when prices and costs have declined for many years.

Hall and Hall (1984) define scarcity in terms of the cost of extracting a resource, which is based on Hotelling's original concepts. Malthusian scarcity is where in-situ stocks are finite and Ricardian scarcity is where stocks are not finite, but costs of extracting them increase as you extract more. Concentrating on Malthusian scarcity, Hall and Hall define Malthusian Stock Scarcity (MSS) where resource stocks are finite but are of uniform quality so that the cost of producing them stays relatively constant with constant technology. However instead of looking at the cost of extraction to determine scarcity, this paper will look purely at the costs of exploration. Extraction costs will be zero. The assumption of zero extraction costs can be modified later, nevertheless this assumption changes the emphasis of determining scarcity away from the costs of producing a resource and toward the cost of finding a resource.

Norgaard looks at the difficulty of exploring for resources in the "Mayflower" problem where information about the location of low cost natural resources is incomplete. When the Mayflower pilgrims came to America, they settled at the first most convenient location possible in New England even though the soil there was not as good as the soil in say the Midwest. If the Mayflower pilgrims had used the available resources optimally in a Hotelling sense, they would have taken the Mayflower to the Gulf of Mexico and up the Mississippi River all the way to Iowa in order to start their farms there. Or at least within a generation or two, the new settlers would have moved all their settlements to the Midwest. At least part of the reason that the Mayflower pilgrims and subsequent generations did not go to the Midwest quickly was because they did not

know that there was good soil there. Their actions imply that finding information about resource location is an unavoidable cost of the supply of natural resources.

Monte Carlo Modeling

In order to understand the economics of mineral exploration and the Mayflower problem, consider a Monte Carlo simulation. Menard and Sharman (1975) show in a Monte Carlo model that if oil explorers in the US drilled random oil wells throughout the US starting in 1859, then the super giant East Texas oil field would have been discovered at the very least by 1902, given the historical rate of exploration. East Texas was actually discovered in 1930. Other giant and super giant fields also undoubtedly would have been found earlier by merely drilling exploration oil wells randomly. The problem with the analysis is that Menard and Sharman know something that the early oil explorers did not know, namely that the East Texas oil field exists. In other words, the Monte Carlo modelers have perfect information that twenty-two giant oil fields in the US exist before they run their model, but the early oil explorers did not have this information and did not know if even one giant oil field existed until the first one was found. Therefore, consider an alternative set up.

A Monte Carlo model is rather like playing roulette where there are black and red slots on the roulette wheel for the ball to fall into. Black is oil, red is dry. The probability of getting black on a bet that costs the amount of money for drilling an oil well depends on how many black slots there are as a proportion of all the slots. If you were to play the gamble, the expected results are exactly equal to the probability of getting black. However, different roulette wheels like different countries and different regions have different probabilities of success. For example compare finding oil in the Persian Gulf to that of Switzerland. In other words, there are different roulette tables with different probabilities.

Assume then that there is a large room full of roulette tables, and that gamblers will come into the room to play the tables. Based on their expected probability of winnings, they will be more willing to bet on the tables with the higher probability of black since those tables will have a higher expected gain. Now assume one more thing. All the roulette tables are covered and mixed before the gamblers enter the room. In that case, the gamblers do not know which tables have a high proportion of black slots and which have a high proportion of red slots. They do not even know if any tables have any black slots. The gamblers have no idea what their chances of winning are or even if there is anything worth betting on or not.

As the gamblers come into the room with the covered roulette tables, they must try to get information about what the tables are like. What strategy will they use? Undoubtedly, the gamblers will wait to see what other gamblers do. If one gambler does make a bet and does get a black slot, chances are good that at least that particular roulette table has more black slots. The gamblers race to that table and start betting. However as the bets are made, every time a slot is hit, it is removed and not replaced. Eventually the black slots are used up and the gamblers will have to leave old tables and start taking their chances on newer tables.

The gamblers do not randomly play on all the roulette tables, as implied by a pure Monte Carlo model. For all they know, all the tables could have only red. There is no way of knowing a priori what the probability is that any black slots exist. In this situation, the gamblers have in their mind

a subjective probability of winning at any given table. However, their subjective probability is different than the actual probability of the table. When the gambler goes to a table where previous gamblers won black, he has information to judge the probability that he also will win based on past experience. That is his own subjective probability. It is based on available information. A gamblers subjective probability will be higher at a table with a past history of winning bets than with an unknown table where there is no history. The subjective probability of getting black at a new table may be lower or even much lower than the actual probability of getting black at that table. Therefore there is a difference between a gamblers or a mineral explorers subjective probability of finding a mineral and the actual probability of finding a mineral, should he drill a well.

This is the Mayflower problem. At first there is very little information and few bets are made, i.e. explorations for minerals. Then as more information is found, more betting occurs because the information helps increase the probability of success until eventually scarcity brings to an end any chance of finding new resources. The mineral economy below is derived from this Mayflower problem. By using this model, we get a very different perspective on how a resource dependent economy will act over time and on the interpretation of the effect of better technology on scarcity.

The Mineral Economy Model

Two economic models describe a resource-based economy in its purest form: the "corn" economy and the "hardtack" economy explained below. For a complete analysis of these models see Page (1979). We can call a third type of resource model the "mineral" economy. The mineral economy model is similar to a hardtack economy model except that the mineral – the hardtack – is hidden. The hidden hardtack must be explored for and extracted before it can be used. To explain the models, consider Robinson Crusoe stranded on a deserted island. In the corn economy scenario, he has some corn with him. He can choose to use varying amounts of the corn to either plant or eat depending on what his intertemporal preference is. If he eats more corn now, he has less corn to plant for future output. On the other hand if he plants more corn, he will have more future output but less to eat right now. In an infinite horizon world, such as a tribe of constant population on the island, a corn economy can last indefinitely.

In the second scenario, Crusoe is faced with a much more sobering possibility of only having a finite amount of hardtack. Again, depending on his personal preference, his years of life and the amount of hardtack he has, he faces several scenarios for exhausting that hardtack. He can choose to eat more now or save his stock and eat more later, but his reserves are limited. He may even not survive long if his supply is too small. If we extend Crusoe's life indefinitely by replacing him with a tribe on the island with a constant population and still a finite amount of hardtack, then that society faces the inevitable dilemma of sooner or later running out of hardtack and dying off. Better technology, though, could overcome such a grave scenario.

However, neither of these scenarios for Robinson Crusoe parallels the real world, where our economies are to a large degree based on underground non-renewable non-recyclable resources, such as oil, coal and natural gas. In the real world, unlike a hardtack economy, these natural resources are not stored in such a manner so that we can quantify them costlessly, the way we can quantify hardtack stores costlessly. Rather, many natural resources are hidden from the economy

until they are found. The hidden resources create an unavoidable cost for finding the minerals. That is an exploration cost. Even if extracting the mineral is costless, there is still an exploration cost implied by the search process that influences the rate of extraction. Using the characteristics of the Mayflower problem, we can create a model for the cost of exploration over time and then use that model to analyze scarcity and how powerful technology really is for overcoming scarcity.

Consider a situation where Robinson Crusoe lands on a deserted island with no food. Assume that previous shipwrecks with no survivors have left hardtack on the island. If Crusoe is able to find these old shipwrecks and the hardtack on them, he can survive by eating the lost hardtack. However, let us further assume that these previous shipwrecks happened many years before Crusoe's shipwreck, such that all the ships have been buried deep in the sand and are not visible from the surface. Crusoe can survive by eating this leftover hardtack, which is his "mineral" resource, if Crusoe can find it. This situation is the mineral economy. In the mineral economy assume there is Malthusian Stock Scarcity where the resources are of constant quality and even free to extract. The only problem is knowing how much resources there are and finding them.

When Crusoe first lands on the island, he must hurry to find food where he can. Because no previous shipwrecks can be seen from above ground, Crusoe does not know if any hard tack even exists underground and if it does exist, how much there is. Nevertheless with no other option, Crusoe takes a chance and digs for hidden hardtack. Eventually he gets a break and finds one shipwreck and manages to find the left over hardtack of that ship. Such a find will give Crusoe new information about where other shipwrecks may be because often times ships will wreck at the same location. This is similar to all the gamblers with the covered roulette wheels all going to the one table where there was a black slot found and betting on it. Therefore, with this new information about one ship's location, Crusoe will be better able to find other ships and his cost of searching will decrease. The more hardtack that Crusoe finds, the more information he has, and the easier it is to find even more hardtack.

Eventually though, because the supply of hardtack is finite, depletion sets in and Crusoe finds less and less hardtack. Therefore, even though Crusoe has more and more information about where the hardtack is, the depletion of the resource base creates higher costs of exploration, since it is hard to find the last few remaining stocks the rate of discovery decreases. Crusoe's supply of hardtack left to be found dwindles until he can no longer survive.

Two long run forces, then, drive Crusoe's mineral economy. First, there is the information effect where the more information Crusoe has about the location of the hardtack, the cheaper it is to find and the more he is able to find. Second, there is the depletion effect where the less hardtack that remains to be found, the costlier it is to find and the less he can find. These forces create a pattern of first an increasing and then a decreasing rate of discovery. Uhler (1976) calls the two opposite forces of information and depletion the information and depletion effects.

An Exploration Information Cost Model

Assume that Crusoe's technology for finding and using the hardtack stays constant and actual extraction is costless. Changes to these assumptions are possible after the basic model is developed. Assume every time Crusoe explores a location for hardtack, he must eat h_c of

hardtack in order to give himself the physical energy to look. This is his cost of exploration effort. If Crusoe searches in 20 locations, he must eat 20 times h_c hardtack. Furthermore, assume for simplicity that when hardtack is discovered in any one location, that it is always the same amount of hardtack, call it h_d . While most minerals occur in large and small loads or pools, rather than constant loads, it is assumed that a large load is the same as a lot of small ones that are near each other. Therefore, hardtack that is left in the ground from previous shipwrecks is always packed in small tins or boxes that are the same h_d size. The tins are separate and must be discovered separately. Smith and Paddock (1984) suggest based on empirical evidence that minerals such as oil occur in large and small pools or loads and that the largest pools or loads of minerals are usually found first and then subsequently smaller pools and loads are found within one region. However, their empirical evidence is not general enough, since in many cases the largest loads of minerals are not the very first reserves found. For example, the East Texas oil field, Prudhoe Bay, and the great Ghwar oil field in Saudi Arabia were not the first oil fields found even though these are some of the largest fields on Earth. In general, small loads of minerals are found first, then large ones and then small ones again. For Crusoe, it is assumed that each tin is separate and equal, however large loads of minerals can be simulated by having lots of tins being close together. When one is found others nearby are easy to find. Hence:

h_c = Pounds of hardtack consumed per exploration location that is searched,

i.e. effort cost.

h_d = Pounds of hardtack found per exploration location when the exploration is

successful. h_d is the pounds of hardtack found in each tin. All tins are

assumed constant for all successful exploration locations.

$h_d > h_c$

In order to discover Crusoe's marginal cost of extraction for any given rate of extraction, it is necessary to know the probability of success for each individual search and how that probability changes as the rate of extraction changes. Crusoe's exploration of any given location is not always successful. There is a probability of success or failure. The probability for Crusoe's success rate is called the probability weight function, P_r , which is modeled formally below. P_r is a function of ultimately recoverable reserves, the current rate of exploration, and information, which is dependent on cumulative discovery. P_r models Crusoe's subjective probability of finding more hardtack rather like a probability coin. Every time Crusoe expends effort to search for hardtack at a specific location, his success of finding more hardtack is like flipping a coin. However, the probability of success is not necessarily 50/50. Instead, the probability weight of the coin can be anywhere from 0/100 to 100/0 for success, depending on Crusoe's subjective probability. That subjective probability depends on information such as how successful previous explorations have been and exploration progress. The subjective marginal benefit of exploration for Crusoe is then $h_d \cdot P_r$ or alternatively the marginal cost is h_c / P_r .

In the Monte Carlo game with the gamblers, there was the actual probability of taking a gamble on the roulette wheel, which the gamblers did not know, and their own subjective probability of gambling at that table. Like the gamblers in an unknown Monte Carlo simulation, Crusoe too has no idea if there is any hard tack at all under ground or, if there is some, where it is. Nevertheless, Crusoe will use whatever information he can garner from past experience to choose the best location possible. His subjective probability, P_r , will change as information changes.

There are two distinct aspects of how information affects Crusoe's exploration process. When Crusoe begins his search for hardtack at the beginning of the day, he will have in his mind all possible information about where hardtack may or may not be. He will begin his search at the location where his subjective probability of success is the highest. That is, Crusoe will explore for hardtack first in the most probable locations. He will continue searching at second and third best locations. Therefore, as the day passes, Crusoe will have a lower and lower probability of success.

During the day, however, Crusoe may also gain new information, which could help his search. For example, Crusoe may discover hardtack and start to see a pattern about where hardtack usually occurs underground. This may increase his probability of success. Therefore, there are two distinct forces that affect the probability of success. One force is where the old information becomes less and less useful in helping Crusoe make successful new discoveries. The other force is where new information discovered during the course of exploration helps Crusoe raise his probability of success. In order to understand these two forces better let us separate them and model them differently. For simplicity, assume that Crusoe can only use one set of information during a given day and that any new information he finds he cannot assimilate until the next day. This will separate the effects of information into a short run (within a day) and a long run (longer than one day) time frame. In other words, Crusoe will use information rather like capital. "Information capital" is Crusoe's accumulated information, i.e. his stock of information. Information capital is like a stock of capital machinery, it cannot change in the short run. Only in the long run can new information be added to the current stock of information, causing the information capital to increase.

Short Run Characteristics of Probability

In the short run, Crusoe has a finite stock of information, i.e. information capital that cannot change, to use for looking for more hardtack. The information capital is a complex data configuration. New information and data cannot be easily integrated into the existing information capital just like a new machinery cannot be easily and quickly integrated into an existing stock of capital. Therefore, all new information cannot be assessed until the next day. However, Crusoe can use the existing information capital to look for hardtack over an infinite combination of places during the current day. He will look for hardtack first in the places where his subjective probability of successfully finding hardtack is the highest and then in second and third best locations. As he looks, though, the probability of success declines. The reason for the decline is because the information capital is subject to the law of diminishing returns which causes the value of that information stock to decrease. In other words, the law of diminishing returns degrades the value of Crusoe's information capital as he uses it so that it is less and less useful the more it is used during the day. The marginal productivity of the information capital declines as effort and therefore output increases. This is similar to how the marginal productivity of

capital itself declines as output increases. The effect of the degrading value of old information is to cause a decreasing probability of success. A convenient formula for P_t to model this short run value of the information capital is the following.

$$P_t = \exp[- Q/L]$$

$$Q = Q(S)$$

where

$$dQ/dS > 0$$

and

Q = the daily quantity discovered or current rate of discovery

S = Effort in terms of numbers of searches per day

L = a long run trend parameter

The short run probability will act as a decline curve as the rate of discovery increases. The rate of effort, S , is an independent variable chosen by Crusoe, which will determine the rate of discovery. If effort increases, discovery increases and probability falls. At the beginning of the day it may take two exploration tries to find hardtack, but as the day wears on, it may take Crusoe ten tries. Therefore, the probability of finding that last tin of hardtack decreases from 50% to 10%, and hence the marginal cost rises. The lower probability of success is due to the diminishing returns on the current information capital which increases marginal cost. Crusoe will tend to look for hardtack during the day until his cost of exploration is close to or equal to his benefit of successful discovery, h_d . Setting the probability as a function of the rate of discovery rather than effort makes the model easier to work with. The more one discovers the resource during the day, the more one uses the current information capital. The more the current information capital is used, the less valuable it is. The less valuable the information capital is, the lower the probability of success. Therefore marginal cost rises.

Long Run Characteristics of Probability

Recall in the Monte Carlo situation above that initial gambles, like initial efforts to find a resource, are very unsuccessful due to a lack of knowledge and therefore a great deal of effort is used to find only a small amount of resource. Eventually, however, with greater information, it takes fewer efforts to find a given amount of resource. Therefore, in the long run, new information will increase the information capital and increase the probability of success, such that the probability of finding the mineral will increase. Concurrently, however, there is depletion. In addition to long run information gains, the depletion effect will cause less of a resource to be found. As a resource depletes to nothing, the probability of finding more of that resource must also decline. Therefore, in the long run, two effects on probability are modeled: the information effect and the depletion effect. See Uhler.

With greater information capital Crusoe can find more hardtack for a given level of effort. Greater cumulative discovery implies greater information capital, which will cause a higher probability of success. This is the information effect. However, with greater depletion, Crusoe will find less hardtack with a given level of effort. Greater cumulative discovery equates to less remaining resources in the ground available to find, which will cause a lower probability of success. This is the depletion effect. The information effect will dominate initially, and the depletion effect will dominate subsequently. The probability weight function as a whole shifts first outward and upward and then inward and downward with cumulative discovery. The result is a small-large-small sequence of the discovery and extraction of hardtack in the long run. These long run effects on probability are modeled using cumulative discovery.

Greater cumulative discovery of hardtack implies that there have been greater exploration efforts, and such efforts must increase the amount of information. Therefore, cumulative discovery is used as the long run information capital indicator. It is also possible to use cumulative exploration as an information indicator, but if unsuccessful search locations actually do provide information, then they will lead to more discovery. Thus cumulative discovery is just as good an indicator of information capital as cumulative exploration efforts. The benefit of using cumulative discovery rather than cumulative effort is that one variable can be used for both the information and depletion effects more simply.

Greater information capital shifts the probability weight function higher. That shift is an information effect shift, where greater cumulative discovery implicitly signals greater information capital. As the stock of undiscovered reserves depletes to zero, though, the probability of finding new hardtack must eventually become zero, because there is no more hardtack left to find. The depletion effect then is where less hardtack reserves make it more difficult to find new hardtack causing the probability weight function to shift down. The depletion effect depends explicitly on greater cumulative discovery, because higher cumulative discovery equates to a lower stock of remaining undiscovered reserves.

In order to model the information and depletion effect, assume the long run trend parameter, L , shifts the probability function P_r in the manner explained above. A likely equation for the trend is M. King Hubbert's life cycle hypothesis (Hubbert 1962). Hubbert's life cycle hypothesis which was used to explain the long run trend of oil production in the U.S. ideally models a mineral economy faced with the Mayflower problem. Hubbert's model has a small-large-small sequence of discovery and production of a mineral that would be expected in the mineral economy. For an economic analysis of Hubbert see Cleveland (1991), Cleveland and Kaufmann (1991), McCabe (1998), and Edwards (1997). Hubbert's original model using L as the trend for current discovery is a time dependent logistics curve as follows:

$$L = a \cdot U \cdot \{1 + \exp[-a(t-t_0)]\}^{-2} \cdot \exp[-a(t-t_0)] \quad (1)$$

where

a = an amplitude parameter. This determines the height

and width of the Hubbert curve

t_0 = The time at which the peak in production occurs.

t = Time.

U = Ultimately Recoverable Reserves

L = The trend of the rate of discovery

However, it is possible to subsume the time element of Hubbert's logistics curve in order to make it a pure cumulative discovery model that can be used to measure the combined effects of information and depletion. Hubbert's cumulative discovery model is as follows,

$$CQD = U / \{1 + \exp[-a(t-t_0)]\}$$

Which can be rewritten as

$$(t-t_0) = \{\ln[U/CQD - 1]\} / -a \quad (2)$$

where

CQD = Cumulative Discovery

Substituting equation 2 into equation 1 gives

$$L = a \cdot CQD - a \cdot CQD^2 / U \quad (3)$$

which can be called the Hubbert trend.

J.J. Wiorkowski [1981] developed a range of logistics curves similar to Hubbert's life cycle curve, using what is called the Richards function (F.J. Richards [1959]). From Wiorkowski and Hubbert, a generalized trend in terms of cumulative discovery can be used to describe L over time. The generalized Hubbert trend is as follows.

$$L = a \cdot CQD \cdot U^{(\mu-1)} / \mu - a \cdot CQD^\mu \cdot CQD / U \cdot \mu$$

and, when $\mu = 0$,

$$L = a \cdot CQD \cdot \ln U / U - a \cdot \ln CQD \cdot CQD / U$$

where

μ = shape parameter, $-1 < \mu < \dots$

Equation 3 was Hubbert's original trend where $\mu = 1$.

The Hubbert trend, L , drives the probability weight function in the prescribed manner hypothesized by the mineral economy. It models an early low probability of success that increases due to the information effect. It then models a subsequent decreasing probability of success due to the depletion effect. In the short run, L does not change so that as Q increases there is diminishing returns to finite information capital causing a decline curve for the probability weight function. The long run trend will cause the short run probability function curve to shift out initially and then inward in later periods.

A Mineral Market Simulation

Since Crusoe does not know how much hardtack is under the ground, it could be one million times his most opulent lifetime consumption or only a weeks worth of food, he cannot perform an intertemporal maximization. If Crusoe's discount rate is zero, he simply lives at a subsistence level. However, for any other discount rate above zero, he just does not have enough information to maximize utility. Nor can a tribe of constant population. As long as a tribe has a rate of discount greater than zero, then they cannot use the Hotelling principle, since they do not know if the resource base will last a thousand generations or less than one. Therefore, a simple Crusoe model cannot be solved. However, if we assume that Crusoe or a tribe believes that the resource is so vast that it verges on being infinite, i.e. that the probability of discovery always goes up in the long run, then there would be no Hotelling rent. The resource is seemingly renewable. Crusoe will each day explore up to the point where marginal cost equals h_d . Consider this possibility more generally.

Assume instead of Crusoe by himself, that there is a large economy and that there is a mineral industry for one particular essential natural resource input into that economy. The market for the mineral is within a larger market place. The marginal cost of finding the mineral for all firms in the industry is:

$$MC = E_c/h_d \cdot P_r$$

where

E_c = cost of effort in the industry

MC = aggregated marginal costs of the industry

$$P_r = \exp(-Q/L)$$

P_r is determined by the industry wide rate of discovery. When the industry extraction rate, Q , increases, P_r decreases due to industry wide diminishing returns to information capital. Note, the industry is made up of many firms and all firms use each others information, therefore, this is an efficient market where all information is available to the other players, similar to the Monte Carlo gambling simulation above. Costs are minimized, profits maximized. h_d is the marginal unit of extraction, therefore let $h_d = 1$ for convenience. The cost of actual extraction is assumed zero.

That assumption can be changed to add an extraction cost that also decreases with time, but the general conclusion will be the same. Therefore in this simulation it is assumed that the aggregated marginal cost includes both extraction and exploration costs. In that case:

$$MC = E_c \cdot \exp(Q/L) \quad (4)$$

This gives the following characteristics:

$dMC/dCQD < 0$ when the information effect dominates

and

$dMC/dCQD > 0$ when the depletion effect dominates

In addition technological effects for supply can be added to equation 3 and 4. Let:

$$E_c = E_{c0} \cdot \exp(-T_c \cdot t)$$

where

E_{c0} = Initial cost of effort in the industry

T_c = Cost technology factor (the percent reduction in costs per year)

Also

$$U = U_0 \cdot \exp(T_u \cdot t)$$

where

U_0 = Initial Ultimately Recoverable Reserves

T_u = Ultimately Recoverable Reserve technology factor (the percent increase in ultimately recoverable reserves per year due to technology)

Consider a simple demand curve for the resource that reflects a growing economy.

$$Q = G \cdot (P)^{-1/3} \quad (5)$$

and

$$G = G_0 \cdot \exp(g \cdot t)$$

Where

G = economic production of the entire economy

G_0 = initial economic production of the economy

g = economic growth factor for the economy

P = price for a given quantity demanded

According to the Hotelling rule, rent will increase over time. However, if uncertainty is large enough this may not happen. See Watkins (1992). For example, if resource prices have been falling for a very long time, and they look to continue to fall for a long time, then producers will set $P = MC$. There will be no Hotelling rent. Producers believe the resource is infinite due to new technology. When technology is thought to be the cause of a long price decline, then it is easy to conclude that technology will continue to improve indefinitely and cause prices to fall indefinitely. In that case, a resource producer maximizes present value not by withholding exploration for, or extraction of, resources, but by producing more now before prices go even lower. The producer maximizes present value simply by producing as much as profitable in the current year irrespective of rent. Producers would generally set $P = MC$.

Consider a model simulation using the following values for equations 3, 4, and 5:

$U_0 = 100,000$

$a = 0.15$

$T_u = 1\%$ per year, i.e. slower than economic growth

$G_0 = 500$

$g = 3\%$ per year, i.e. faster than the rate of technological growth of the resource

$E_{c0} = 1$

$E_{c13} = 1$, E_c is held constant in the initial 13 periods to give the system

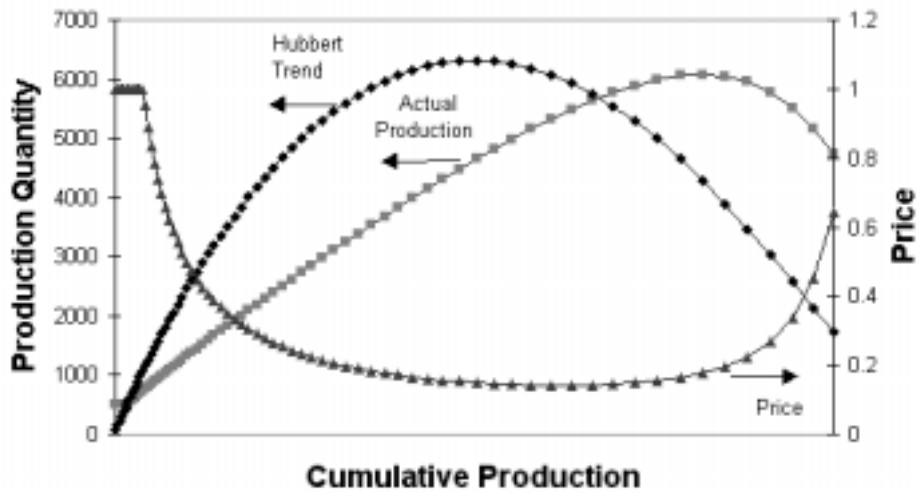
stability

$T_c = 5\%$ per year after the first thirteen years.

In the simulation, the technology to increase ultimately recoverable reserves is improving at a slower pace than economic growth. However, the effect of technology on the resource base to increase its recoverable reserves is unknown to the market and remains unknown until late in the exploration process. Therefore the market sets $P = MC$. In each period, Q and P are solved using equations 3, 4 and 5, then the effects of technology are added. Since equation 4 and 5 are indeterminate for Q , Q_{t-1} is used to solve for Q_t . The difference between Q_t and Q_{t-1} is small enough so that the substitution creates no problem.

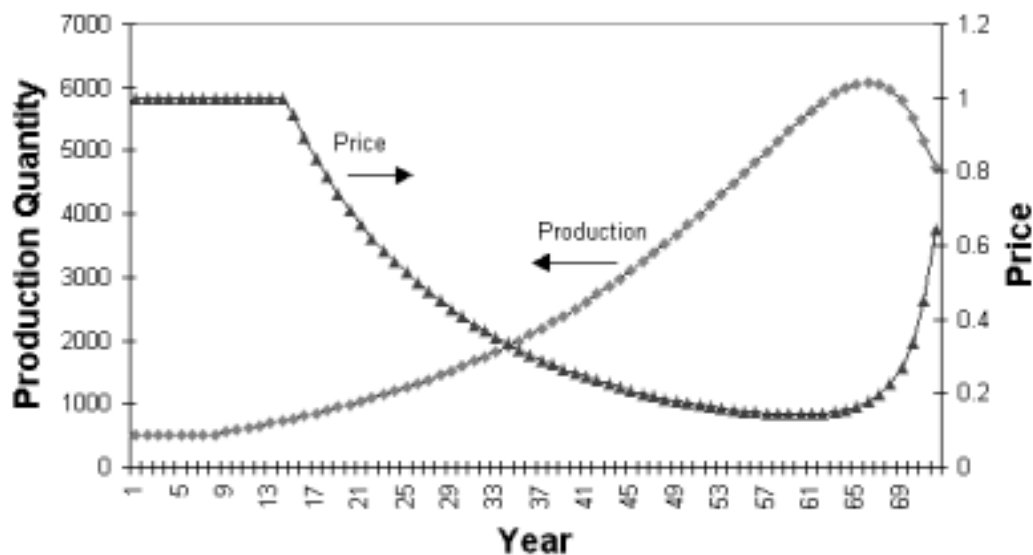
The results of the simulation can be seen in figure 1 and 2. In figure 1, the supply Hubbert trend (L), the quantity produced (Q) (which is the equilibrium of supply and demand), and price (P) are shown as a function of cumulative production (CQD). Actual production is less than the supply Hubbert trend potential, i.e. the Hubbert trend, for most of the cycle. It is only after the supply Hubbert trend reaches its point of decrease that production finally gets close to and goes above the Hubbert trend. The Hubbert supply trend is only the *trend* of supply, it does not determine absolute supply. The actual supply can be above or below the Hubbert trend although supply becomes increasingly inelastic above the Hubbert trend. Scarcity is revealed only when production goes well above the Hubbert trend. At that point, the price finally starts increasing and production finally starts decreasing. Before that point, it is not possible to know how forceful technology is for increasing potential reserves. Suddenly, scarcity is revealed but unlike the Hotelling model, there is no forewarning.

Figure 1. Price, Production, and Hubbert Supply Trend as a Function of Cumulative Production



In figure 2 is shown the price trend as a function of time. Notice that the price, as well as the costs that determine price, which is not shown, decline for many years before the price finally increases. Furthermore, during those price decreases, quantities extracted of the resource are constantly increasing. In fact it is possible to model a situation where price decreases and supply quantity increases continue for hundreds or even thousands of years before the price finally rises and quantities finally decline. However, the change from one trend to the other can happen within a few years even though the trends before the change over lasted for hundreds of years. In other words, the information effect can dominate the depletion effect for a very long time before depletion finally and dramatically dominates. If you add to the information effect technology, then it takes even longer before depletion dominates. Nevertheless, the power of technology to overcome scarcity is not known until it is revealed late in the cycle.

Figure 2. Price and Production as a Function of Time



The problem with using price, cost or quantities produced as a measure of scarcity is that up until the point where demand crosses the Hubbert trend, it is unclear how powerful technology is for decreasing scarcity. Only when prices start actually rising due to the depletion effect can society know how big the Hubbert cycle is and how much technology has stretched the resource base. Before that point in time, the information effect obscures the size of the resource base and the true power of technology for reducing scarcity. An additional problem is that since price declines for a long period of time before the price shock, it is unclear what substitutes for the resource are available and at what price. There has been no gradual increasing price and therefore no signal to inventors of when a backstop will be needed, and no signal to consumers of when the backstop will be needed to be used. The market is not properly prepared for the change over.

However, once the price reaches its lowest level in figure 2, producers of the resource will realize that the resource is a lot more scarce than they had previously thought. They will suddenly understand that the price will start increasing and they will cut production in order to maximize intertemporal profit via the Hotelling principle. This cut in production will cause the price shock to be much more severe. In addition, Reynolds (1997) shows that the backstop price of a resource can unexpectedly rise due to the loss of entropy subsidies. It is conceivable that after one hundred years of price decline and production increase, that a resource can have a ten or one hundred fold price increase within a year or two, with a corresponding decline in production. Given that short run elasticities of demand and substitution are much more inelastic, than long run elasticities, this can create quite a problem for an economy to say the least.

Conclusion

In the Hotelling model, there is perfect information about the backstop price, the quantity of the resource, the demand for the resource, and the cost of extracting the resource. With perfect knowledge, rent of a resource increases at the interest rate up to the backstop price. Uncertainty theory can be added to the Hotelling model to try to find out how trends of prices and quantities change under various assumptions when the resource base is unknown. However if there is enough uncertainty it is almost impossible to use the Hotelling principle. In this model is shown how the uncertainty of the resource base can obscure the actual trend of scarcity and the true power of technology and create a price shock. Such a price shock can occur after a very long price and cost decrease simultaneous to a long production increase. This model shows theoretically that empirical data on cost and price declines as well as data on increases in quantities of extraction do not necessarily imply decreasing scarcity. Indeed, such data may not even be useful for warning about impending price shocks. What is even more foreboding is that once producers do know that scarcity is much greater than previously thought, the price shock will become all the more severe. Resource producers will cut back production due to increasing prices causing prices to increase even further. The so called back stop price may be much higher than expected especially since the loss of entropy subsidies can make the backstop price increase substantially.

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