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Futures Markets, Price Stabilization and Efficient Exploitation of Exhaustible Resources

ERWIN BULTE[1], JOOST M. E. PENNINGS[2] and WIM HEIJMAN[1]
[1] *Wageningen Agricultural University, Department of General Economics;* [2] *Wageningen Agricultural University, Department of Marketing and Market Research, P.O. Box 8130, 6700 EW Wageningen, The Netherlands*

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Abstract. Markets for natural resource futures contracts and cash forward contracts experience a rapid growth. According to theory, this should result in more efficient resource depletion, implying that price formation is more consistent with Hotelling's rule. The rationale of this stabilization effect is briefly discussed. Next, we analyze the impact of expanding futures markets on the behaviour of individual resource owners trading on the cash market. Using a simple pulse extraction model, we demonstrate that the expected time of depletion can shift to the present or the future, and that utility of exploitation can go up or down, as market prices are stabilized.

Key words: efficiency, futures markets, natural resource management, price stabilisation, risk aversion

1. Introduction

Trading of natural resources on futures markets has a long history (Catania et al., 1989), but especially in recent years these markets have experienced a substantial increase in the use of price risk management instruments (see Figure 1). Price risk management methods range from standard futures contracts trading to simple verbal understandings between buyers and sellers. Futures trading involves buying and selling contracts on an organized commodity exchange, as a hedge or for speculative purposes. Managing price risk is important for commercial firms with respect to their planning decisions. Resource prices in the cash market have fluctuated widely in the past (e.g. World Resources, 1994–1995), resulting in price risk.

This paper builds on previous work by Solow (1974) who provided an intuition of price instability, by Sundaresan (1984) who provided a theoretical investigation of equilibrium spot and futures price behaviour in a non renewable commodity market, and by Mueller (1989, 1994) who investigated the effect of hedging and geological uncertainty on the behaviour of a firm exploiting a non-renewable resource. The latter two articles focus on the optimal use of futures markets by resource owners. Here we investigate an important, though empirically not undisputed, side effect of futures trading, namely reduced spot price volatility on the extraction decisions of resource owners. We focus on pulse extraction, rather than efficient extraction paths and optimal hedging behaviour.

We explore whether expanding futures markets will enhance or reduce profitability of resource exploitation for individual resource owners. In addition, the impact on the timing of extraction is addressed. Another important objective of this paper is to present a methodology with which these questions can be addressed.

This paper is organized as follows. Section 2 discusses the effects of a growing futures market on the price path. Section 3 explores the impact of the futures market on the behaviour of individual resource owners. The conclusions ensue.

2. Price Fluctuations and Efficient Depletion

Hotelling (1931) demonstrated that, under some conditions, benefits of exploiting an exhaustible resource stock are maximized when the growth rate of price equals the discount rate. Then, shifting extraction from one period to another cannot increase the net present value of exploitation. Empirical work by, for instance, Barnett and Morse (1963), Barnett (1979), Halvorsen and Smith (1991), Farrow (1985), Heal and Barrow (1980), Smith (1978, 1981) and Agbeyegbe (1989) indicated that actual depletion may not be in accordance with the Hotelling rule.[1] Berck (1995) concludes that there is clear evidence for capital market considerations in a few resources, and much less so for the rest.

Some work has incorporated price uncertainty in the analysis. From Pindyck (1980, 1981) we know that uncertainty over future prices can affect the production rate of risk neutral resource owners for two reasons. First, if marginal extraction costs are a non-linear function of the production rate, stochastic price fluctuations will, on average, result in increases or decreases of cost over time (due to Jensen's inequality), so that cost can be reduced by speeding up or slowing down the extraction rate. Second, fluctuating prices increase the option value of *in situ* resources, which is an incentive to hold back production.[2] Lewis (1977) demonstrated that the rate of extraction under conditions of price uncertainty depends on the resource owner's willingness to accept risk, and that risk averse resource owners will tilt the extraction path towards periods where variations are relatively low.[3] Finally, Gaudet and Howitt (1989) show that deviations from the Hotelling path are optimal for risk averse owners when the covariance between the marginal utility of consumption on the one hand, and the difference between the rate of net price increase and the interest rate on the other hand, is not equal to zero.

It can be assumed that, for risk averse owners, the utility of exploiting a resource stock declines when resource prices fluctuate. One response to fluctuating resource prices was the establishment and expansion of futures markets for natural resources. Recent trade volumes for two arbitrarily selected metals on the London Metal Exchange are illustrated in Figure 1.

The role of futures markets in stabilizing spot prices has been widely discussed in the literature. When deciding about current and future supply, resource owners have

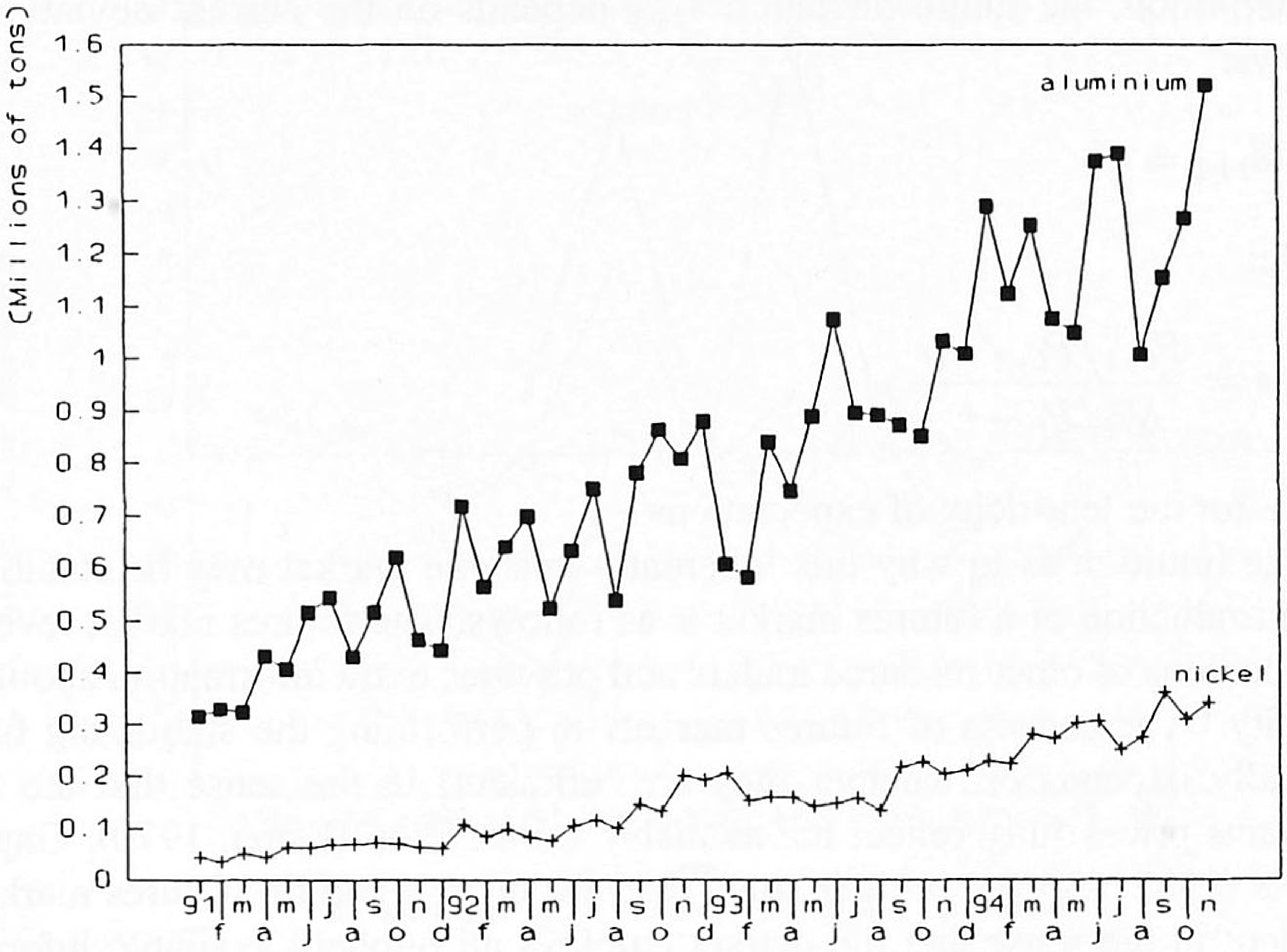

Figure 1. Volumes of aluminium and nickel traded on the LME futures market (Jan. 91–Nov. 94).

to form expectations about future prices. They can try to form rational expectations based on future supply and demand conditions, but their expectations can also be based on the behaviour of current prices. Unstable price paths can be explained if the majority of the resource owners forms expectations in the latter way. If, for instance, prices are expected to rise faster than prescribed by the Hotelling rule, resource owners may respond by withholding supply which leads to a speculative run-up of prices that is self-reinforcing. Symmetrical reasoning applies when prices rise too slowly. Depending on which way we start, initial disequilibrium is tilted either toward excessive current dumping or toward speculative withholding of supply (Solow, 1974).

This process, which would explain severe upswings and downswings in resource prices, only holds if the elasticity of expectations, defined as the percentage change in expected future price divided by the percentage change in the current price (Fisher, 1988), exceeds unity. For our purposes we adapt this concept slightly: the percentage future deviation from the growth rate of the price in excess of the discount rate divided by the percentage current deviation from the growth rate of the price in excess of the discount rate. Assume that price p_{t+1} at time $t+1$ equals price at time t multiplied by 1 plus the rate of interest r plus the future deviation δ_{t+1}. Hence:

$$P_{t+1} = (1 + r + \delta_{t+1})P_t. \tag{1}$$

By definition, the future deviation δ_{t+1} depends on the current deviation δ_t as follows:

$$\delta_{t+1} = \epsilon\delta_t \tag{2}$$

where:

$$\epsilon = \frac{\dot{P}_{t+1}/P_{t+1} - r}{\dot{P}_t/P_t - r} \tag{3}$$

with ϵ for the 'elasticity of expectations'.

The intuition as to why this inherently unstable market may be stabilized by the introduction of a futures market is as follows. The futures market reveals the expectations of other resource traders and provides extra information about future scarcity.[4] The success of futures markets in performing the stabilizing function critically depends on whether they are 'efficient' in the sense that the futures contracts prices fully reflect the available information (Fama, 1970). Gupta and Mayer (1982) showed in their study that, for copper and tin, futures markets are efficient in the sense that the market employs all publicly available information in forming expectations about future spot prices. Likewise, Weiner (1989) and Dominguez (1989) find that today's futures or forward price is the best predictor of tomorrow's oil price. For this reason, commodity futures exchanges have been termed clearing centres for information.

The existence of futures contracts trading increases the speed by which information is disseminated, which tends to equalize the flows of information to current and potential futures and cash market participants. Price movements on the cash market will be less rigorous because resource owners can base their decisions on better information. In addition, futures markets provide facilities for hedging and forward transactions as a temporary substitute for transactions on the spot market. Hence, resource owners can move out of the spot market if they consider market conditions unfavourable. Turning to the futures market, they automatically remove potential pressure from the spot market, thereby reducing price effects there (Tomek and Gray, 1970). Futures markets can contribute to more than just short-run price stabilization, because a wide range of delivery time points (maturity of the futures) exists. Maturities may range from days to decades (Stoll and Whaley, 1993), though it is expected that the futures market gets increasingly thin as the time of delivery is further into the future.

Not only the information function of futures markets, but also the speculators attracted by the futures markets will stabilize spot prices. The more speculators that are attracted, the more likely it is that forecasting errors will be compensated for, including those of the traders of the actual commodity. The result is more informed decision making and prices that are more closely representative of basic supply and demand conditions. This, in turn, implies that the stock of unextracted resource should become more sensitive to changes in the return to the stock. The

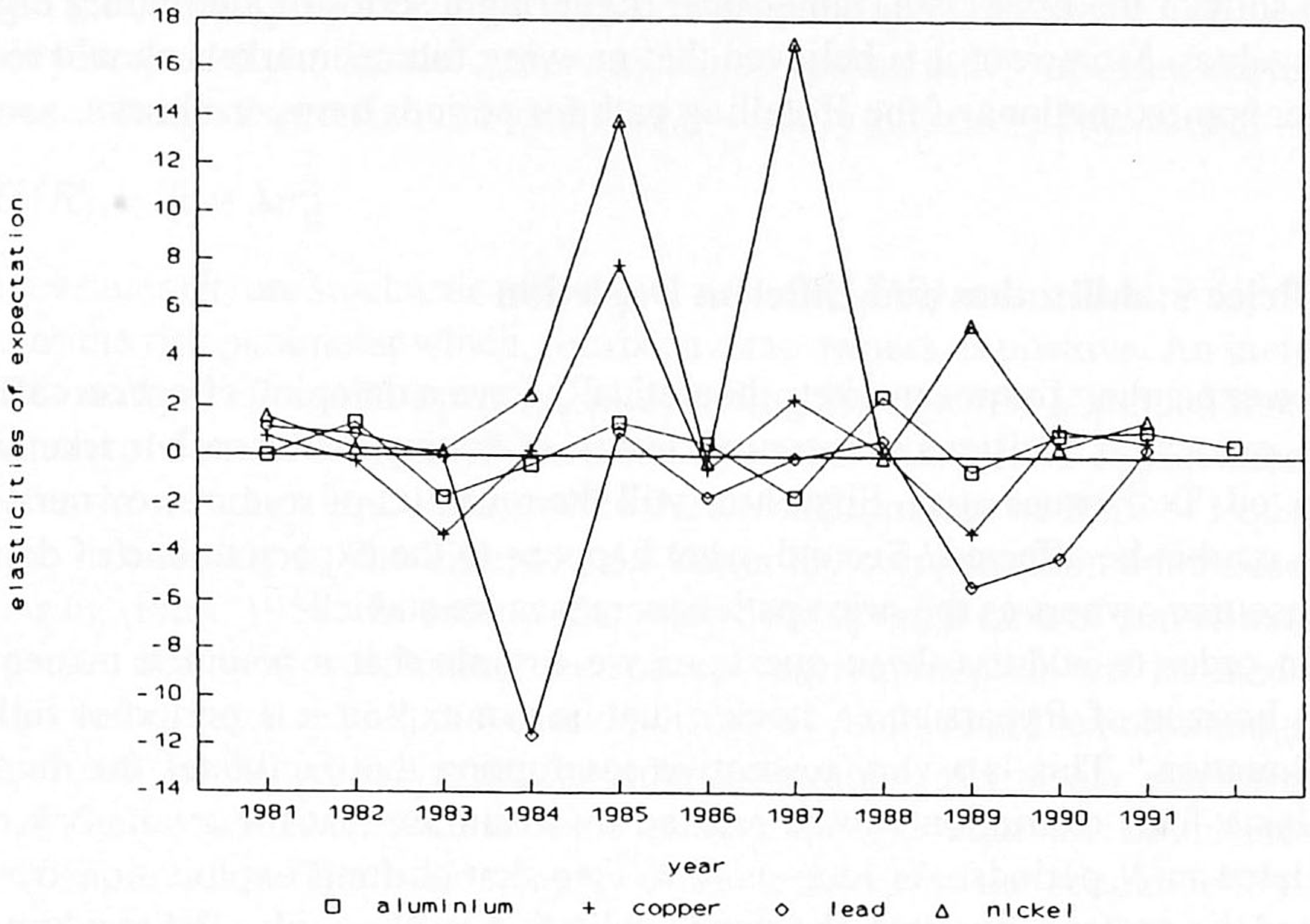

Figure 2. The elasticity of expectations for some selected metals (1981–1992).

increase in stock sensitivity means that the stock will absorb a larger proportion of demand and supply shocks than it did previously, thereby reducing spot price volatility. Recent research supports the hypothesis of reduced spot price volatility when futures contracts are introduced (Netz, 1995; Gilbert, 1989; Peck, 1976), although it has also been reported by others that the stability hypothesis may be rejected (for instance Uriskill et al., 1991).

As Appendix 1 indicates, more stable prices imply that the elasticity of expectations takes on values in the interval $(-1, 1)$. If this is the case, δ_t approaches zero and the Hotelling path will be approximated more closely as time passes. Thus price stabilization should, *ceteris paribus*, be reflected in a declining elasticity of expectations over time. Figure 2 displays the development of ϵ for the period 1981–1992. Due to the small number of observations, no additional statistical analysis is carried out. Figure 2 serves as an illustration only.

At first sight, there seems little support for the hypothesis of a declining ϵ_t. However, interpretation of the graph is difficult because the *ceteris paribus* condition is likely to be violated. There may have been important real world phenomena that are neglected in the simple model, and which are important determinants of short-run price fluctuations. It is important to observe that in the real world, the Hotelling equilibrium path will be subject to a variety of shocks too.[5]

Even with a system of perfect futures markets and other price risk management instruments, the cash market will experience some price fluctuations. We expect, however, that due to 'less elastic expectations' the shocks will manifest themselves as a shift of the price path, rather than triggering a series of alternating high and low values. Moreover, it is believed that growing futures markets should result in better approximations of the Hotelling path for periods between shocks.

3. Price Stabilization and Efficient Depletion

Since expanding futures markets theoretically have a damping effect on cash markets, extraction decisions of resource owners operating on the cash market will be affected. Two issues arise. First, how will the revenues of resource owners on the cash market be affected? Second, what happens to the expected time of depletion of resource owners as the price path becomes more stable?

In order to address these questions we assume that a resource owner has a time horizon of T years and a stock q that he can exploit in 1 period of full force exploitation.[6] This is a very restrictive assumption that facilitates the numerical analysis. This restriction can be relaxed by assuming that the total stock can be depleted in N periods. As long as $N < T$ so that shifting exploitation from one period to another is possible, the same qualitative results apply. The results are less pronounced as N approaches T.

The resource owner wants to maximize his utility of exploiting the stock resource. This problem can be solved with a dynamic programming model. We resort to a numerical approach, based on forestry models with fluctuating prices (e.g. Brazee and Mendelsohn, 1988).[7] It is assumed that resource owners tailor their exploitation decisions to variations in prices, implying that exploitation takes place when market demand and supply conditions are such that prices are relatively high. In periods of depressed prices, typically no exploitation takes place.

With cash prices following a stochastic process the resource owner must decide between a certain price in the current period and unknown prices in the future. A risk averse decision make will prefer a riskless investment whose expected return is equal to the expected return of a risky investment. It can be argued that riskiness in the case of selling natural resources is a function of the standard deviation of price fluctuations: the more heavily prices fluctuate, the riskier the market. The most common tool to analyse decision making under risk is the expected utility model.

The difference between the expected return on the risky investment and the return on the riskless investment that leaves the resource seller indifferent between the two choices is defined as a risk premium. The return on the risk-free investment, equal to the expected return on the risky investment less the risk premium, is defined as the certainty equivalent of the expected return on the risky investment (Robison and Barry, 1987). The magnitude of the risk premium thus depends on the level of risk aversion of the individual resource seller as determined by his utility function and on the level of risk as determined by the standard deviation of price fluctuations.

Since the current price is known with certainty, the resource owner will balance the utility derived from certain current revenues against utility of expected future revenues. Assume that resource owners have a utility function of the form:[8]

$$U(R) = R - \lambda\sigma_R^2 \quad (4)$$

where revenues (R) are stochastic with expected value $E(R)$ and variance $\sigma^2{}_R$. Also, λ denotes the risk parameter which, for risk averse owners, is positive. An increase in the fluctuations of resource prices while holding the expected revenues constant thus reduces the attractiveness of the offer. The term on the LHS of Equation (4) represents the certainty equivalent, while the second term ont he RHS of Equation (4) is the risk premium. The higher λ, the larger the compensation demanded for risk bearing (Pratt, 1954). In order to determine the optimal time of extraction and the expected utility of exploitation, the concept reservation price will be used.

In this price search model, the reservation price is defined as the minimum price to be 'offered' by the (cash) market in order to economically justify extraction of the stock. This reservation price is based on the expected return one could earn by delaying exploitation. The basic strategy of the resource owner should be to mine his resource today only if utility derived from current extraction is at least as great as the utility of the expected present value of exploitation in all possible future periods. The expected utility derived from postponing exploitation thus determines the reservation price in each period.

When the current price is below the reservation price for that period, the resource owner should respond by exploiting nothing. If, however, the current price exceeds the reservation price, he will exploit all of his stock. Because prices below the reservation price are refused, the expectation of future prices is taken over the truncated distribution with the reservation price as the lower point of truncation. Hence, the 'accepted' prices have a higher expected value than the 'offered' prices, which implies that the reservation price path is located above the current price path in time.

In the numerical model, prices are again assumed to be determined exogenously for the individual resource owner. Prices vary substantially and unpredictably from period to period. As in Brazee and Mendelsohn (1988), we assume that the error structure around the empirical model's predictions is normally distributed, and moreover that resource owners can determine the expected mean and standard deviation of future prices (for instance by observing past prices). Future prices are assumed to be drawn randomly from the distribution thus known. It is assumed that a new independent random price is established every period (for reasons of simplicity it is assumed independent of last period's price, which will be realistic only if the periods considered are not too short).[9]

In the last period (T), if the resource owner still has his stock left, his optimal behaviour would be to simply sell q at the prevailing price. The expected price ($\bar{p}$) for this period is known from the distribution. Any part of the resource remaining in the ground from that period onwards is believed to have no value for the resource owner. For other periods, the decision whether or not to exploit is made by comparing the current price and the reservation price for that period. For period K, the reservation price (P^*) of q units is obtained as follows:

$$\begin{aligned} U(P_K^* q)e^{-rK} &= \int_{P_{K+1}^*}^{\infty} [U(R)f(P)\mathrm{d}P]e^{-r(K+1)} \\ &+F(K+1)\int_{P_{K+2}^*}^{\infty} [U(R)f(P)\mathrm{d}P]e^{-r(K+2)} + \ldots \\ &+F(K+1)F(K+2)\ldots F(T-1)U(\bar{P}q)e^{-rT} \end{aligned} \tag{5}$$

where R_t is revenues $P_t q_t$; $U(.)$ is the (expected) utility of (un)certain revenues; $f(P)$ is the probability of price P occurring that year; and $F(t)$ is the probability that the stock is not exploited at time t (implying that the offered price is below the reservation price). When prices are greater than zero, this probability is calculated as:

$$F(t) = \int_0^{P_t^*} f(P)dP. \tag{6}$$

Of course, the probability that q units will have remained in the ground to time T is the product of the probabilities that they have not been exploited from period 1 through period $T-1$. This is indicated in Equation (5) by the sequence of Fs. Equation (5) is a dynamic programming problem that can be solved recursively from period T to period 1, given the specification of $E(P)$ and σ_p.[10]

If, for instance, price in the first period is equal to 50 measurement units, q equals 1 quantity unit, T is arbitrarily taken as 50 years, the expected real price displays a small trend of 3% per period, and the standard deviation of the resource price (σ_p) is constant and equal to 30, then the reservation price path can be determined unambiguously. Recursively applying Equation (5) results in the reservation price path as displayed in Figure 3. The upper line in the graph represents the reservation price, whereas the lower line simply represents expected price. Time in years is on the horizontal axis, and prices in measurement units on the vertical axis.

The expected time of depletion of the resource is calculated by multiplying the chance of extraction for any period t (which is $(1 - F(t))$) by the corresponding period, multiplied by the probability that the stock has not been extracted in previous years, and then summing these terms. Hence:

$$T^* = \sum_{t=0}^{T} \left((1 - F(t))t \sum_{i=0}^{t} F(i) \right) \tag{7}$$

The numerical analysis is repeated several times to allow for different degrees of price fluctuations, $\sigma_p = 10$, 20 and 30 where larger fluctuations correspond with

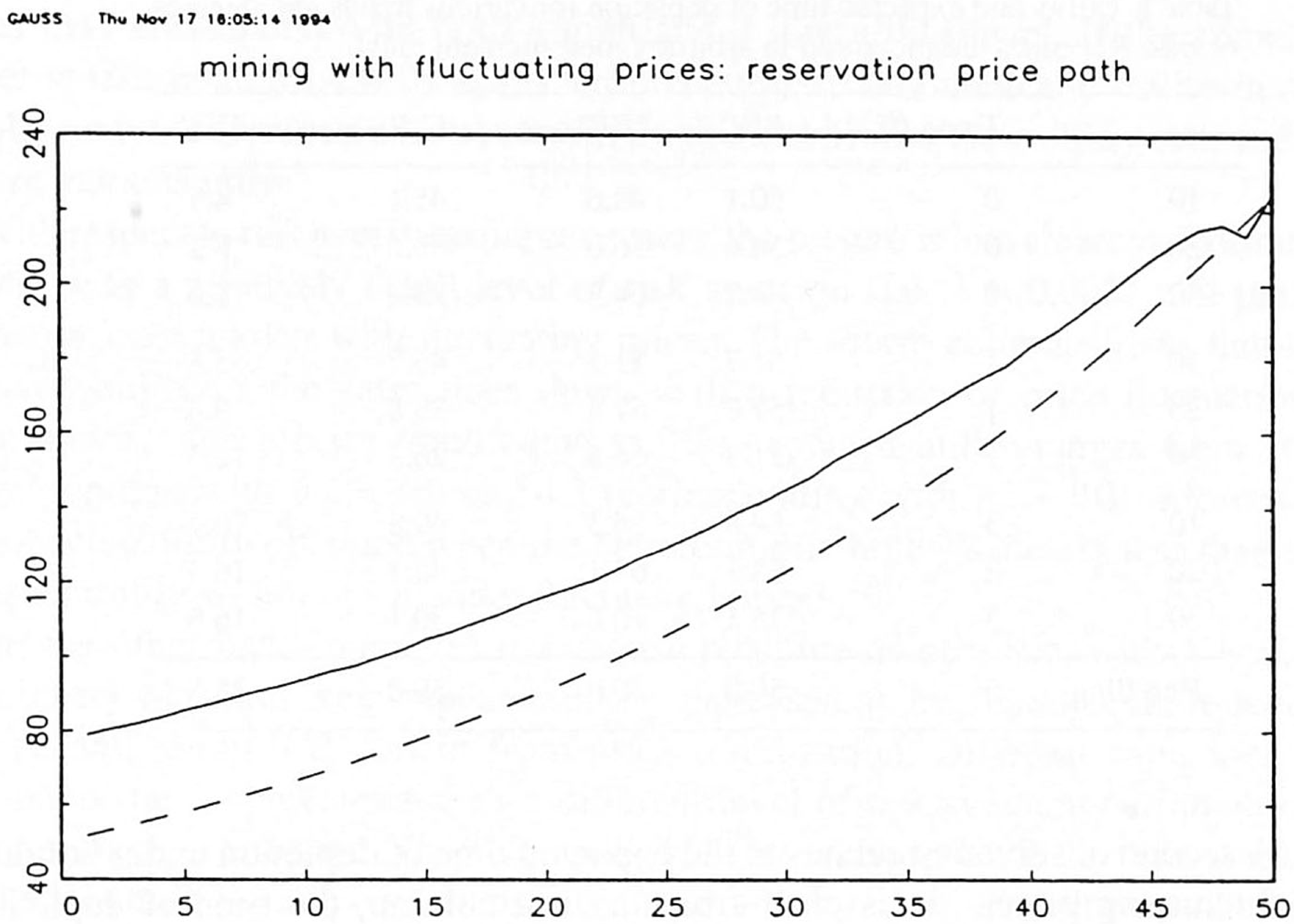

Figure 3. Reservation price path (the solid line) and expected prices (the dotted line).

less stabilization by futures markets, and different trends in resource prices. The discount rate, or the growth rate of the stable Hotelling price path, serves as an upper bound for trend values of an unstable path. The discount rate is arbitrarily selected to be 5%, and trend values of 3%, 1% and 0% have been used for the unstable cases. Here, relatively high trend values correspond with increased influence of futures markets.

The results of the various iterations are presented in Table I. The expected time of depletion and profitability for the Hotelling rule is given in the bottom row of the table.[11] $E(R)$ is expected revenues from selling, $U(R)_\lambda$ is the utility corresponding to these expected revenues as determined by Equation (4), given a specification of the level of risk aversion of the resource owners (λ). Finally, T^* denotes the expected time of extraction. Again it is assumed that the initial price is equal to 50 units, $q = 1$, and in addition that extraction is costless and takes place in one period.

It is clear from the last column that a strategically acting resource owner is an environment with fluctuating prices shifts extraction to the present when compared to expected extraction under the Hotelling rule. The expected time of exhaustion when the resource owner is completely indifferent between exploiting now or alter is 25.5 years, whereas the expected time of depletion of a strategic resource owner in a market with fluctuating prices is variable (depending upon the various parameter values), but smaller.

Table I. Utility and expected time of depletion for various trends and degrees or risk. Revenues are measured in arbitrary measurement units.

σ_p	Trend (%)	$E(R)$	$U(R)_{0.005}$	$U(R)_{0.050}$	T^*
10	0	50.1	49.6	45.1	4.7
20	0	58.6	56.6	38.6	8.2
30	0	68.8	64.3	23.0	11.0
10	1	51.7	51.2	46.7	5.8
20	1	59.8	57.8	39.8	9.4
30	1	71.3	66.8	26.3	12.3
10	3	54.8	54.3	49.8	10.7
20	3	65.1	63.1	45.1	16.3
30	3	75.1	70.6	30.1	16.6
Hotelling	5	50.0	50.0	50.0	25.5

A second observation relates to the expected time of depletion under conditions of fluctuating prices. As is clear from the last column, the time of depletion is postponed as the growth trend of prices gets greater, implying that the resource owner is compensated somewhat for leaving the resource *in situ*, and the price fluctuations are greater.

As discussed in the previous section, the expectation is that expansion of futures markets will result in a growing trend-parameter, until finally the Hotelling trend is achieved. From that point of view, futures markets will postpone depletion. However, our analysis suggests also that expanding futures markets reduce price fluctuations, thereby counteracting the effect mentioned above. Hence, it is not clear whether establishment of futures markets will postpone depletion of resource owners. The reverse may very well be true for strategic sellers.

Third, expected revenues ($E(R)$) are reduced as the use of price risk management instruments expands in our model (see the third column): the less pronounced are the price fluctuations, the less are the benefits of mining. For instance, the expected revenues of selling resources on a market without an upward price trend and with $\sigma_p = 30$ are equal to 68.8 units of measurement, whereas the expected revenues of selling when the Hotelling rule holds is just 50. The increasing trend of resource prices resulting from expanded futures markets will only partially compensate for this adverse effect. As is clear from Table I, the first effect will definitely outweigh the second. The intuition behind the first effect is that an increased spread in offered prices implies that the price can reach higher values in good times. Since the increased number and severity of lower prices can be truncated and therefore ignored, increases in spread tend to raise the expected revenue from accepted prices.

Depending upon the shape of the utility function of the individual resource owner, high expected revenues obtained under conditions of heavily fluctuating prices may correspond with both a high and a low utility level. If the resource owner is risk neutral (λ = 0), expected revenues are automatically utility in our simple model. Therefore, risk neutral individuals will find their utility reduced as futures markets grow.

With respect to risk averse resource owners, the picture is less clearcut. Resource owners with a relatively small level of risk aversion (i.e. λ = 0.005) will prefer to operate on a market with fluctuating prices. The fourth column shows that the expected utility of the sales goes down with a reduction of price fluctuations. For instance, with a price trend equal to 3%, expected utility ranges from 70.6 (corresponding with σ_p = 30) to 54.3 (corresponding with σ_p = 10). Moreover, the expected utility obtained when the Hotelling rule holds is clearly less than the expected utility within reach under fluctuating prices.[12]

On the other hand, there are risk averse resource owners (i.e. with λ = 0.05 and higher) who find their expected utility increased as fluctuations are reduced. This second group will benefit from price stabilization. Different categories of resource owners, characterized by a different level of risk aversion will therefore have conflicting interests. The risk averse resource owners will try to persuade the risk neutral resource owners to participate in futures trading, whereas the risk neutral resource owners have an interest in preventing risk averse resource owners from entering the futures market.[13]

Since exploitation in our model typically takes place in one period, a resource owner who decides to sell a part of his stock forward, automatically restricts himself to selling the remaining part of his stock ont he cash market in that period too. His expected revenues may decline, as compared to the case where the resource owner strategically waits for a period with high prices. Given a certain degree of risk aversion, however, this may make sense. But it is important to recognize that hedging part of the cash market position is not longer optimal for all risk averse resource owners. Therefore it is expected that a share of resource owners will not become involved in hedging, whereas others will. This does not, however, affect the general conclusions.

Two final caveats must be discussed. First, a crucial assumption of the current analysis is that both the stable and the unstable paths have an identical starting point. In reality, this would be extremely accidental. Shifting from an unstable path to a stable path will result in an instantaneous downward price shock if, for instance, the total stock is very large and/or the choke price of the resource is low (for a simple explanation, see Pearce and Turner, 1990). If this occurs, expected utility is less and depletion is accelerated. Likewise, switching from an unstable to a stable price path could lead to an upward price shock, and then the reverse effects will occur. Therefore, a conclusion must be that effects of growing futures markets are to be determined for each resource separately.

Second, it can be argued that even highly risk averse resource owners can be represented by a model with $\lambda = 0$. The argument is, in this very simply model, that resource owners can simply refrain from exploitation when prices are low. They do not need to sell when prices are low,[14] hence they do not face price risk. This would imply that each and every one of the strategic resource sellers will suffer from the stabilizing effect of expanding futures markets, and that not a single resource owner should consider to hedge future cash positions himself. In reality, however, the assumption of full exploitation in just one period will often be too strict. If resource owners exploit their stock over a certain time interval and extraction decisions are less flexible (due to, for instance, fixed costs in exploitation), the rationale for hedging increases. From the fact that futures markets for natural resources have grown considerably in recent years, we can deduce that fixed costs in extraction are important, and that the potential beneficial effects of fluctuating prices as described here are at least counteracted to a certain extent.

4. Conclusions

There has been an increase in the use of price risk management instruments in natural resource markets. For example, demand and supply of futures contracts and cash forward contracts for metals have risen rapidly in the past decade. In theory, this will increase the efficiency of exploitation for the sector as depletion will be more consistent with Hotelling's rule and price fluctuations will reduce, but the empirical support for this hypothesis is still somewhat ambiguous. Provided that futures market have a stabilizing effect on spot prices, some resources owners will benefit from these effects, while others will find that their opportunities have worsened. Therefore we concluded that at the individual level, the effects of futures trading can be either beneficial or costly, depending on the degree of risk aversion of the resource owner. The effect of price stabilization on the time of depletion is also ambiguous. More stable prices on the one hand compensate the resource owner somewhat for postponing extraction, while on the other hand it reduces the strategic incentive to hold resources for speculative purposes. We conclude that it is very difficult to assess whether the impact of increased futures trading on resource exploitation is desirable, or not. This impact will have to be assessed empirically on a resource-by-resource, and individual-by-individual basis.

Acknowledgment

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Appendix 1

Because $\delta_t = \delta_0 \epsilon^t$, and with $\beta_t = 1 + r + \delta_t = 1 + r + \delta_0 \epsilon^t$, it follows:

$P_t = \beta_t P_{t-1}$,
$P_t = \beta_t P_{t-1} = \beta_t \beta_{t-1} P_{t-2} = (\beta_t \beta_{t-1} \beta_{t-2} \ldots \beta_1) P_0$,
$\beta_t \ldots \beta_1 = (1 + r + \delta_0 \epsilon^t)(1 + r + \delta_0 \epsilon^{t-1}) \ldots (1 + r + \delta_0 \epsilon^0)$.
So, if $t \to \infty$, then,
if $|\epsilon| > 1$: p_t unstable, and
if $|\epsilon| < 1$: p_t stable.

Further, we can deduce:
If $\epsilon = \pm 1$, then $p_t = p_0 (1 + r \pm \delta_0)^t$, so:
if $\delta_0 = 0$: p_t stable, and
if $\delta_0 \neq$: p_t unstable.

Table A1 gives all the possibilities depending on values for δ_0 and ϵ, without rigorous mathematical proof.

Table A1. Ten possible combinations of δ_0 and ϵ and their effect on the price path.

	δ_0	ϵ	Stable/Unstable	Oscillations	Actual price path above or below Hotelling path
1.	$\delta_0 > 0$	$\epsilon > 1$	Unstable	No	Above
2.	$\delta_0 > 0$	$\epsilon = 1$	Unstable	No	Above
3.	$\delta_0 > 0$	$0 < \epsilon < 1$	Stable	No	Above
4.	$\delta_0 > 0$	$-1 < \epsilon < 0$	Stable	No	Above
5.	$\|\delta_0\| > 0$	$\epsilon = -1$	Unstable	Yes	Below
6.	$\|\delta_0\| > 0$	$\epsilon < -1$	Unstable	Yes	Below
7.	$\delta_0 < 0$	$-1 < \epsilon < 0$	Stable	No	Below
8.	$\delta_0 < 0$	$0 < \epsilon < 1$	Stable	No	Below
9.	$\delta_0 < 0$	$\epsilon = 1$	Unstable	No	Below
10.	$\delta_0 < 0$	$\epsilon > 1$	Unstable	No	Below

Notes

1 Although it should be noted that the work of Barnett and Morse, Smith, Heal and Barrow and Agbeyegbe was based on price statistics, rather than proxies of rent, which would theoretically be correct under more general conditions than analysed by Hotelling. Slade (1982) demonstrated that U-shaped prices may be compatible with exponentially rising rent, when technological developments lower marginal extraction costs. Stollery (1983) worked with rent data and found empirical support for the Hotelling rule.

2 Low future prices may make production of the resource unprofitable. In that case, future production does not take place, and extraction costs need never be incurred.

3 More specifically, when variations in returns are proportional to the quantity extracted, the risk averse resource owner tends to tilt the extraction path to the future.

4 The futures price of a commodity with a fixed supply is always below the expected future spot price, which is called normal backwardation (Park, 1985).

[5] Examples include that (1) new deposits are unexpectedly discovered, (2) new substitutes are unexpectedly developed, (3) the demand curve suddenly shifts, or (4) new cheap extraction methods are applied. The equilibrium price path should reflect the revised expectations with respect to future scarcity at once. This sudden revision will cause a drop in resource price (as, for instance, actual new discoveries in a certain period exceed expectations), or an upward shock (as actual discoveries lag behind expectations).

[6] We assume that, for instance due to economics of scale, rational exploitation always takes place at full force. In addition, we assume that storing exploited material is costly, so that exploited material has to be sold at the prevailing price in that period.

[7] The assumed risk neutral foresters. We will build on their work to include risk aversion.

[8] The qualitative results are similar for other utility functions that order risk attitudes based on the trade-off between expected value and variance. The current specification is selected for computational simplicity.

[9] This assumption is tentatively checked for iron ore, aluminium, copper and nickel from 1975–1990 (data from world Bank 1991). For nickel and aluminium the autocorrelation function (ACF) and partial autocorrelation function (PACF) prices showed no significant autocorrelations at any lag. Therefore we conclude that the assumptions of stationarity and non-autoregressiveness are not rejected for some resources. For iron ore and copper, the autocorrelation functions indicated that first-order autocorrelation exists. The model can be elaborated by allowing for serially correlated prices. If prices are auto-regressive, the price distribution is conditional on current and previous prices. Notationally, the analysis would be slightly more complex and the gains of adopting a 'reservation price' policy would then be less. For a discussion about price distributions and reservation price paths, see Brazee and Bulte (1995).

[10] The simulation procedure is programmed in GAUSS.

[11] If the Hotelling rule holds, the net present value of revenues (R) of exploiting in any period t is $P_0 e^{rt} e^{-rt} q$, which is simply equal to $P_0 q$. This implies that the probability of harvesting in any period is constant and equals $1/X * 100\%$. The expected time of depletion is given by: $1/2(X+1)$.

[12] Table I also shows that in the extreme case of no trend and low fluctuations the opportunities of acting strategically may be so small that economic performance could be increased by shifting to a 'Hotelling regime'. Increasing fluctuations, however, would be even more beneficial.

[13] Note that the effects described in this section can be caused by other factors than growing futures markets. If, for instance, because of improved education the share of strategic sellers within the total population of resource owners rises, the effect will be similar as expansion of the futures market: price fluctuations will be less pronounced (withholded supply in periods of depressed prices and extra supply in periods of high prices by many small resource owners will have a dampening effect on the price path) and the trend parameter will increase. Likewise, if resource owners improve their expectations with respect to future prices in time, this will result in reaching a stable price path eventually (Fisher, 1988).

[14] The exception to this rule is, of course, the final period when the resource owner is committed to extract his stock.

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