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Steady-state growth in a Hotelling model of resource extraction

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Abstract

This paper re-examines the Hotelling model of optimal nonrenewable resource extraction in light of stock effects and technological progress. We assume functional forms for cost and demand so that the solution to the Hotelling problem is a steady-state consistent with the empirical observation that the growth rates of market prices have remained zero over a long period of time. We use data on 14 minerals from 1970 to 2004 to estimate the supply and demand functions using SUR and 3SLS and to test the model. We validate the model for 8 of 14 minerals.

Keywords: Hotelling; Nonrenewable resources; Resource prices

1. Introduction

The basic Hotelling model of nonrenewable resource extraction predicts that the shadow price of a resource stock, which is equal to the market price minus marginal extraction cost and serves as an economic measure of resource scarcity, should grow at the rate of interest [8]. This prediction is commonly known as the "Hotelling rule."[1] Assuming constant marginal extraction costs and no technological progress, among other conditions, resource prices should be increasing over time. Real world prices do not follow this pattern, however. Empirical studies have shown that mineral prices have either been roughly trendless over time or have been stationary around deterministic trends with infrequent structural breaks.[2] This paper reconciles Hotelling's theoretical model with empirical evidence on world mineral prices.

The Hotelling rule may not be a good guide to the actual behavior of mineral prices over time for several reasons. In this paper we focus on two possible explanations: "stock effects" and technological progress.[3]

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[1]See, for example, Krautkraemer [9] for a recent survey of the literature on nonrenewable resource scarcity.

[2]See Krautkraemer [9] and references therein, Pindyck [17], and Lee et al. [10], as well as Lin [12,13] for the case of oil. Slade [20] has shown that mineral prices have followed a U-shaped price path between 1870 and 1970s, but the coefficients on the quadratic trend are not robust to the period of estimation [2]. From the 1970s through 2004, prices have been nonincreasing.

[3]In addition to stock effects and technological progress, the Hotelling model excludes several other factors. New discoveries, for example, expand the known stock of resource reserves and decrease the price through stock effects. Other factors include adjustment costs and capacity constraints due to the capital-intensive nature of mineral industries, market imperfections in the extractive industries, stock

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Stock effects increase extraction costs and are consistent with rising resource prices, while technological progress lowers extraction costs and causes prices to decline.[4] Slade [20] accounts for both of these effects in her theoretical model explaining U-shaped price trends. We expand Slade's theoretical model by estimating demand and supply functions and by allowing for a steady-state solution to the Hotelling model. We also expand the empirical analysis by using a more recent data set.

The simple Hotelling model assumes that extraction costs do not depend on the stock of reserve remaining in the ground, or equivalently, on the cumulative amount of resource already extracted. In fact, the original work by Hotelling [8] assumes that marginal extraction cost depends neither on the extraction rate nor on the remaining stock. Many researchers have followed this set of assumptions, while others have assumed that marginal extraction cost is an increasing function of extraction but independent of stock [22]. However, extraction costs will likely increase as more of the resource is extracted and fewer reserves remain [4].

Several reasons account for this phenomenon. Extraction costs rise if the resource is extracted from increasingly greater depths. For oil, greater extraction cost goes hand-in-hand with declining well pressure. Moreover, oil as well as other minerals come in different grades. Cheaper grades are likely to be mined before more expensive grades become economical, again leading to increasing extraction costs with cumulative stock extracted. Adding a stock effect to the classic Hotelling model causes shadow prices to rise less slowly than the rate of interest, but market prices still increase over time [11].

A second important reason for why the Hotelling rule may not adequately describe the actual behavior of world mineral prices is technological progress. Innovation enhances the extractive capacity of firms and decreases extraction costs over time.

In the next section, we combine stock effects and technological progress to develop a theoretical Hotelling model consistent with the often-cited stylized fact that mineral prices have remained constant over a long period of time. We then confirm this fact using data on 14 minerals over the period from 1970 to 2004. Section 3 estimates and tests the model's main proposition. We confirm the model's validity for 8 of 14 minerals. The final section concludes.

2. A theoretical model of resource extraction

2.1. The basic Hotelling model

In this section, we present a theoretical model of optimal nonrenewable extraction under perfect competition. We ignore inventories and assume competitive resource markets. We also ignore any common access problems that may arise in perfect competition.[5] Following Pindyck [16], we assume a large number of identical firms that act as price takers. This is equivalent to assuming that a social planner or a state-owned monopoly has sole production rights and sets a competitive price. The assumption of perfect competition may not be realistic for some nonrenewable resources such as oil, tin or nickel. Oligopolistic and monopolistic market structures may produce a bias towards conservation [19]. We abstract away from these problems in favor of tractability of our model.[6]

The notation follows closely that used by Weitzman [24]. Let $t \in [0, \infty]$ index time. At time t, the supply of the mineral is given by $E(t)$, the total extraction flow in tons per unit time at time t. Let $X(t)$ denote the total

(*footnote continued*)
effects on the benefit side caused by decreased environmental services due to resource extraction, and the ever present uncertainty. See Krautkraemer [9] for a further discussion of these factors.

[4]See also Farzin [4] for a general discussion of these effects.

[5]Sinn [19] presents a model of exhaustible resource extraction in which storage facilities are used as a result of the common-pool problem.

[6]Allowing for market power does not necessarily reconcile the theory with the data. For instance, according to Salant's [18] Nash–Cournot model with a cartel and a competitive fringe, the real price of oil increases monotonically for both constant and increasing marginal extraction costs. On the other hand, in Loury's [14] Cournot model, the present value of price net of the constant extraction costs declines over time. Moreover, minerals' markets that may seem to have market power may actually behave very much like perfectly competitive ones. For example, Agostini [1] finds that prices in the U.S. copper industry prior to 1978 were close to the levels predicted by a competitive model, even though the copper industry was highly concentrated.