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The green paradox of the economics of exhaustible resources

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HIGHLIGHTS

- The green paradox is a direct application of Hotelling's rule from the economics of exhaustible resources.
- Hotelling's analysis was a profound contribution to economic thought but evidence for it is weak.
- Hotelling-style analysis assumes incorrectly that production can be rearranged at will among time periods.
- Technological and geological features of oil production make the prediction of the green paradox unlikely.

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ABSTRACT

The green paradox states that an increasing tax on emissions of carbon dioxide, consonant with the expected increase in their marginal damages, may induce oil producers to shift their production toward the present and thereby to exacerbate the problem of climatic change. The model is based on Hotelling models of resource use that do not take the natural and technical features of oil production into account. Natural features include the decline of production through time according to a decline curve. Technical features include the requirement to sink investment in productive capacity. A model of a profit-maximizing firm indicates that, if these features are taken into account, the prediction of the green paradox is unlikely.

1. Introduction: The meaning of the green paradox

In discussions of appropriate policy responses to climatic change, the role of fossil fuels, especially oil, takes centre stage. There is a current sense of urgency to begin to reduce consumption of these fuels. A method favoured by some economists is a tax on emissions of carbon dioxide, in essence on oil use. Since the marginal harm inflicted by emissions is expected to increase over several decades, a proposal consistent with much of environmental economics is that the tax should be announced as increasing through time, in step with the marginal damages.

Suppose that a global tax on fossil fuels were implemented, and that governments worldwide could commit to the future schedule of taxes deemed appropriate to balance the costs and the benefits of oil use. Would this development be salutary in the context of climatic change?

One theoretic development holds that it may not. The *green paradox* states that dynamic influences may thwart the intent of the tax by giving producers an incentive to shift production toward the present. It would thereby cause an increase in damages in the short and medium terms.

Oil is an exhaustible resource. The economics of exhaustible resources is expressed through Hotelling's rule. In its simplest form the rule states that in equilibrium the net price, the price net of marginal costs and marginal taxes, rises at the rate of interest. The argument for the green paradox is a direct application of the rule, which prescribes the optimal timing of the extraction and use of exhaustible resources. By changing the *relative* net values of a unit of oil at different future dates (as compared to the original equilibrium without the tax) the tax may induce producers "to tilt" their production toward the present. Greater emissions in the present and medium term may be induced. Since there is a fixed quantity of fossil fuels in the earth, the greater emissions come at the expense of emissions in the long-term future. (In the simplest models there is a one-to-one shift in production.) By then, other means to attack the climate problem may be available. Paradoxically, the tax, intended to help to solve the problem of climatic

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change in the short and medium runs, may exacerbate it, and yet provide only limited relief in the long run.

The green paradox merits attention from environmental economists because the theoretic issue is recast by climate change; it becomes the timing of a tax instead of the equity and apparent efficiency of having the "polluter pay" directly for the marginal damages caused. The policy issue is whether the tilt toward the present, described in theory, can be expected to play out in practice.

The present paper expresses doubts about the analysis that gives rise to the green paradox. These doubts are the product of doubts about the applicability of Hotelling's rule. The analysis draws attention to features of extraction such as sunk investments and production constraints, which are neglected in Hotelling models. The paper begins with a brief explanation of Hotelling models. Then it reviews the application of Hotelling analysis to effects of the tax on flows. Later, it interprets a survey of the empirical analysis related to Hotelling's rule. Finally, it considers technological and natural features of oil production. These features make the oil industry more complicated than envisaged in Hotelling models. Definitive answers are not possible, but indications are that the effects of a carbon tax may more likely be conventional than paradoxical.

2. Hotelling models

Hotelling's (1931) model of *the economics of exhaustible resources* is a profound contribution to economic thought. It provides five major insights:

- Exhaustible resources are a form of capital.
- The price of the resource is determined in a dynamic equilibrium that regulates both the flow of the resource to market and the holding of the resource as an asset.
- The timing of decisions is of central significance and warrants careful analysis.
- Resources are subject to the usual market failures, viz. monopoly, externality and informational asymmetry.
- Exhaustibility in itself does *not* entail a special form of market failure. In particular, competitive markets are not subject to a myopic inability to allocate an exhaustible resource in way that efficiently balances the interests of the present and the future.

In the Hotelling model, units of the resource are viewed as being available to society for extraction at any time, at a known cost that depends on the quantity extracted and possibly other factors. A striking analytic result of the model is *Hotelling's rule*: under certain assumptions, in a dynamic, competitive equilibrium the price net of marginal cost of an exhaustible resource rises at the rate of interest. (Under other assumptions the rule is more complicated.) The rule can be proved through optimal-control analysis and is mathematically incontrovertible.

The economic reasoning behind the rule is even more striking. Consider what is called herein a *type-one* Hotelling model of an exhaustible resource, in which extraction costs depend only on the quantity of the resource that is currently being extracted. In this case, the extraction cost of $q>0$ units of the resource is given by some function $c(q)$. This function is assumed to be increasing, so that extracting more units at a given time costs more, and to be convex, so that it becomes ever costlier to extract additional units.

As argued by Solow (1974), the owner of a resource who wishes to maximize net present value is led to re-arrange extraction such that what is earned by the marginal unit in each time period is equal in present-value terms. If the marginal unit at one time gains less than at another time, present value can be increased by reallocating output from the period with the lower gain to the one with the higher gain. In symbols, let $p(t)$ represent the price at time t, r represent the prevailing rate of interest and $\mu(t)=[dc(q)/dq]_t$ represent the marginal cost of production. Suppose that a proposed path of extraction is such that, for times t and s during production

$$D(t,s)=\frac{p(t)-\mu(t)}{(1+r)^t}-\frac{p(s)-\mu(s)}{(1+r)^s}>0.$$

Then a unit of production can be re-allocated from time s to time t, at a net gain of $D(t,s)$.

The re-allocation can be done repeatedly, so long as an inequality holds, at a net gain each time. Ultimately, a constant, λ say, is determined such that for all times t and s during which extraction takes place

$$\frac{p(t)-\mu(t)}{(1+r)^t}=\lambda=\frac{p(s)-\mu(s)}{(1+r)^s}.$$

Another re-arrangement yields that

$$p(t)-\mu(t)=\lambda(1+r)^t \tag{1}$$

the *net* price (price net of marginal cost) rises at the rate of interest. Eq. (1) expresses Hotelling's rule. The discussion stresses that Hotelling's rule is an arbitrage condition for the use of an asset, through the allocation of extraction, over different periods of time.

Often it is assumed that the marginal cost is constant, so that for some number β, $c(q)=\beta q$. In this case, for any value of q or t, $\mu(t)=\beta$. The assumption allows for developing sharp mathematical results, including the early insights of the green paradox by Sinclair (1992) and Ulph and Ulph (1994), as well as some more-recent ones.

A remarkable feature of Hotelling's original paper is that he also considered what may be called a *type-two* model. In type-two models, cost depends on the total available reserve, Q say, as well as current output, and is written $C(q,Q)$. The properties of this cost function are that it is an increasing, convex function of output q and a decreasing, convex function of available reserves Q. (Costs are lower if reserves are higher.) Also, $C(0,Q)=0$ for any value of Q. A type-two model delivers less sharp theoretic results than a type-one model: There is still arbitrage among marginal units of the resource but the influence of the remaining reserve on cost yields a more complicated expression of Hotelling's rule. The rule is expressed in terms of the discounted sum, over the future of production from the resource, of the increases in cost that arise because current production affects future costs through depleting total reserves. Though harder to work with theoretically, type-two models are considered to be more realistic.

The function $C(q,Q)$ has been a workhorse of empirical research in economics since the late 1970s. Several theoretic analyses have also utilized it. In the main, however, theorists have resorted to the simpler function βq. The same observations are true of the green paradox: Although some authors have used the function $C(q,Q)$ in theoretic work, the simpler function is the foundation of the more striking conclusions.

A key point is that either function implies that at any time any level of extraction q is possible if one is willing to incur the current marginal cost. (If cost is βq, an unbounded level of output can be had at the constant marginal cost β). Consistently with the nature of arbitrage in Hotelling models, output can be shifted at will over time. There is no impediment to tilting output toward the present.

3. The green paradox

Even though the analysis of extraction with cost $C(q,Q)$ is more complicated than with cost βq, Sinn (2008) deftly uses arbitrage