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An economic model of long-term phosphorus extraction and recycling

Demet Seyhan*, Hans-Peter Weikard, Ekko van Ierland

Environmental Economics and Natural Resources Group, Wageningen University, Netherlands

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ABSTRACT

Phosphorus (P) is a macronutrient necessary for life. In the form of phosphates it presents a mineral resource that we depend on, having no substitute for its fertilizer use. These limited reserves of P are depleting globally, and maintaining or improving food security will require careful long-term use of the resource. We study here the extraction and recycling of P with an optimal control framework, and develop a resource-specific model. We determine time-paths for extraction and recycling when both technological progress and a geological stock effect drive the supply of P. Demand is described by a hyperbolic function with a strictly positive lower bound reflecting the key properties of the resource, its non-substitutability and its essentiality. We obtain three insights: (i) Although essential and non-substitutable, P resources will be depleted due to a strict minimum consumption level. Recycling could postpone depletion costs and maintain a minimum consumption forever but at rising marginal costs. (ii) Although extraction depletes the resource and increases its scarcity over time, we observe that on an optimal path the price can fall, which will increase extraction. This underlines that market prices cannot serve as reliable scarcity indicator and fail to support resource augmenting technologies. (iii) If the shadow price is used as scarcity indicator, it would provide incentives for recycling even under declining primary resource prices.

1. Introduction

During the past century, population growth and changing life styles rendered soil nutrient content and its natural renewal insufficient to support world food demand. In the 1840s Justus Liebig stressed the urgency of replenishing soil nutrients, and provided the means of doing so by creating “chemical manure” to overcome the nutrient barrier (Hofmann, 1876). Today some hundred million tonnes of fertilizers are used annually to provide food for the growing global population, and another barrier is appearing: phosphorus (P) resource depletion.

In this paper we approach the problem of P-depletion in two steps: Firstly, we treat P as a non-renewable and essential resource. We apply optimal control theory to address the issue of depletion. We observe that a special value arises from the essentiality of P resources, and this suggests immediate efficiency increases in use. Secondly, we raise the question, whether and when a recycling technology should be introduced.

Below, we first discuss stock depletion of non-renewable resources in general with respect to the fixed stock and full substitutability paradigms of resource economics (Section 1.1). Then, we provide a short account of recycling as applied to non-renewable resources (Section 1.2). We close Section 1 with an elaboration on the research questions.

1.1. Global phosphorus stock and depletion

Contrary to nitrogen that is abundant in the atmosphere and can be fixed by some plants or synthesized as ammonia in an industrial process, phosphorus, the next widely used macronutrient, can only be extracted from its mineral reserves and there is no substitute for its use in agriculture. Therefore, P-scarcity does set a natural limit on long-term food production, which, among others, depends on the size of the resource stock. Herring and Fantel (1993) see a vital link between phosphate rock and the world food supply. Considering the reserve base data and annual demand growth rates of 1–2%, they conclude that presently known mineral reserves will be depleted within the next 50–100 years. Earlier Goeller and Weinberg (1976) investigated the total stock of P in the earth’s crust. They estimate that the lifetime of the complete stock of P is an order of magnitude higher, but once this is depleted, agriculture would become intolerably costly even with a renewable energy source.

Both resource economists and natural scientists have addressed the basic question of general resource depletion, i.e. whether and under which conditions an economy relying on resources can maintain its production and consumption level, and they have expressed, optimistic or pessimistic views. Much of the difference

* Corresponding author. Tel.: +31 317 482222; fax: +31 317 482 494.
E-mail address: d.seyhan@gmail.com (D. Seyhan).

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in perspectives has arisen from the basic assumption of a fixed natural resource stock that is to be depleted. As early as the 19th century economists such as Malthus (1798) and Jevons (1866) expressed pessimism about future resource availability. They saw population growth as the main factor that depletes an aggregate, fixed and limited resource stock. In 1970s, concerns about depletion were revisited by natural scientists who employed system analysis to warn about the future course of the economy, in particular by showing the environmental impacts of resource use and the risks of depletion (Meadows et al., 1972; Hubbert, 1976).

Some 20th century economists chose not to use this notion of a fixed and aggregate resource stock in their approach. Their reasons and so their views on resource availability differ from one another: According to Georgescu-Roegen (1971a,b, 1979), a pessimist, the natural resource endowment is indeed limited but it is wrong to expect price to signal the depletion of an aggregate stock, (i) because the natural increase of entropy that is speeded up through an overconsumption of resources remains uncaptured and (ii) because it is impossible to fully substitute natural resources by man-made capital. He concludes that therefore physical quantities and not the price need to be analysed to make resource scarcity measurable. On the other hand, Zimmermann (1933), an optimist, has defined resources not as fixed physical entities bound to deplete, but rather as being functionally and dynamically defined in response to human knowledge, arts, wants and social objectives. This functional definition seems to be well supported by a rich record of real-life experiences as summarised by Ayres and Warr (2009), along with a discussion of the properties and limits of technological progress. Although less enthusiastic than Zimmermann, the Austrian School and neoclassical economists embraced the idea of technological progress and substitution. Von Mises, for example, "rejected the notion of a special economic rent accruing to resources that he defines as fixed in the aggregate" (Bradley, 2007).

According to the current paradigm that has prevailed as the standard approach, extractions from a non-renewable resource deplete its stock. The seminal cake eating model of resource extraction results in a strictly declining extraction over time until the resource is exhausted (Hotelling, 1931). As a result, on an optimal path, ever decreasing units of an aggregate called the 'non-renewable resource' is passed on to the future until full depletion. More recently, economists such as Dasgupta and Heal (1974), Solow (1974) and Hartwick (1977) responded with models that involve substitution possibilities and technological progress. The key issue was whether the natural resource could be substituted by capital. Generally, if the substitution elasticity between resource and capital is higher than or equal to unity, then practically the resource is substitutable and production can be maintained forever. A sufficient capital stock is built up while the resource stock asymptotically approaches zero; see Toman et al. (1995) for a concise summary. The case of a non-substitutable resource remained open, although Dasgupta and Heal (1979) underlined the importance of technological progress with low elasticities of substitution.

Similar to these growth models we study an essential and depletable resource. Following the approaches by Schulze (1974), Slade (1982), Farzin (1992) and Krautkraemer (1998), our extraction model accounts for a stock effect together with technological progress in mining and shows the possibility of non-monotonous optimal extraction paths. Our contribution is to develop a 'resource-specific' model with three characteristics: (i) we rule out substitution, (ii) we introduce a minimum consumption requirement and (iii) we allow for recycling. By imposing these characteristics, our resource-specific model is no longer burdened with the discussion of aggregating or substituting various resources.

It is due to two reasons that P depletion cannot be treated within the full-substitution paradigm. Firstly, no other element can take its place in the biological processes to serve its vital functions as a cell component of living organisms. Secondly, there are high losses in the anthropogenic use of this resource, especially in agriculture (Baccini and Brunner, 1991), and so extraction irreversibly depletes the resource. Phosphate rock depletes through weathering and consumption and gets dispersed in the environment. That is, the primary P-resources entering the system get rapidly transformed to a state from which their regeneration takes about 10^8 years, implying that nature does not provide the human ecology with a cyclical flow of P. Therefore, in order to prolong the lifetime of the P-reserves, technologies need to be developed that reduce dispersion of P into the environment.

1.2. Recycling as a form of resource augmentation

According to Weinstein and Zeckhauser (1974) recycling of non-renewable resources could in the short term be motivated by disposal pressures, and market forces would anyway bring about some recycling. Weinstein and Zeckhauser ask whether we can rely on the market to bring about the optimum amount of recycling for the long-term. This question receives more importance in our case of an essential resource. The long-term perspective requires correct signals of increasing scarcity over time to trigger a negative feedback on resource depletion. But is recycling related to the scarcity increase of the primary resource, and what is the correct measure of scarcity? For Carlsen (1973), increasing extraction and refinement costs in the future will shift the economic activity in favour of recycling. Yet, he claims that a lag effect could cause severe economic disruptions in the supply of key minerals. Finally, André and Cerda (2006) show that recycling affects the dynamics of natural resource use.

Among all mineral resources, how does P relate to recycling and what is our definition of recycling for the purposes of this study? P is to some extent recyclable and does not get lost after use like fossil fuels do. Compared to metals, some of which are recycled to save energy, P cannot be substituted. General models of recycling have featured energy savings and waste minimisation. Here, recycling is seen as a process that returns some of the P which is contained in output goods back into productive use. The concept is introduced into a dynamic model as a resource augmenting (non-dispersive waste treatment) technology that creates a secondary resource as the partial substitute of the primary resource that is non-renewable. In practice, as a technology of valorisation that is decentralised, recycling could also help reducing market power in concentrated resource markets.

1.3. Research questions

We study the case of phosphorus using a resource-specific intertemporal optimization model, where P is an input to agriculture, and welfare is derived from food consumption. A similar resource-specific economic model has recently dealt with recycling of phosphorus resources, where a monotonously increasing Hotelling-type price path drives the extraction (Weikard and Seyhan, 2009). In this paper we extend the basic model by introducing technological progress in extraction and a stock effect that renders extraction more expensive as the stock is depleted. We check efficiency and welfare criteria from a utilitarian perspective to answer the questions: (i) Do we observe a gradually increasing economic scarcity on the way to depletion that is manifested in the resource price? (ii) Would recycling contribute to resource lifetime (or long-term benefits), and how?