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ANALYSIS

Distribution of phosphorus resources between rich and poor countries: The effect of recycling

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ABSTRACT

Phosphorus (P) is an essential input into agriculture with no substitute. Thus international and intertemporal P allocations greatly impact food security which requires increased food production for a growing world population. As high quality phosphorus mines are being depleted, recycling gains importance and developed countries explore new technologies for P recycling. We analyse the effects of P recycling in developed countries on global extraction of rock phosphates and the imports of developing countries. We build a resource extraction model for a competitive fertilizer market that reflects the fact that most developed countries have P-saturated soils while soils in many developing countries are P-deficient. Our model extends a simple cake eating problem. We consider two types of countries that differ in demand and recycling options. We find that P recycling in developed countries does not only prolong the resource life-time, but it also increases the developing counties' share of the resource.

1. Introduction

Phosphorus (P) deserves special attention among all resources. P is necessary for life as a macronutrient. It is a factor that limits growth in many ecosystems. Phosphorus has always been in short supply in agricultural production (Steen, 1998) and it must be provided as an external input for sustained crop production (IFDC, 1998). Deficiencies of P in agricultural soils impair agricultural productivity and jeopardise food security (Runge-Metzger, 1995). Phosphorus for fertiliser is extracted from limited reserves of rock phosphate and there is no alternative to depletion in the long-term. Different projections suggest that these reserves will be exhausted in another 60–130 years (Steen, 1998; Wagner, 2003).

Because natural forces dominate the mobilization of the elemental phosphorus (Klee and Graedel, 2004), the anthropogenic use of the resource is burdened with high losses, especially in agriculture (Baccini and Brunner, 1991). Moreover, increasing market integration of the agricultural sector and urbanisation have separated the geographical link between production and consumption processes. As a result, large amounts of P drawn from agricultural soils end up in the sewer systems of cities. In this setting P recycling from wastewater can have the double function of mitigating the depletion of resource stocks and reducing P emissions into receiving waters (Schmid Neset et al., 2008). As recycling is never complete, the ultimate depletion of phosphate reserves cannot be avoided. However, careful long-term stock and flow

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management could slow down resource depletion (Seyhan, 2006). Thus, given the non-substitutability and the non-renewability of rock phosphate, an efficient P management is of strategic importance. Moreover, rock phosphate reserves are concentrated in few countries, with West Sahara and China having the largest reserves (FAO, 2004).

The aim of this paper is to study the impact of P recycling in developed countries on the distribution of the resource between developing and developed countries and on the depletion of global reserves. We set up a model to compare resource allocations over time and between countries with and without the use of recycling. Several key features are built into our model: (i) the essentiality (non-substitutability) of the resource, (ii) its non-renewability and (iii) the possibility to recycle in developed countries with a limit to recycling. We focus our analysis on recycling in developed countries because the treatment of waste and wastewater generates P-rich wastes as by-products. These are the basis for P recycling. In most developing countries, by contrast, wastewater treatment is virtually absent (Scott et al., 2004) which leaves little scope for the implementation of P recovery or recycling from wastewater.

Our analysis links an international with an intergenerational allocation problem to determine equilibrium market allocation paths with two types of P-importing countries and a competitive mining industry. Countries of the first type, for simplicity referred to as *rich*, have developed and implemented technologies to recycle, while countries of the second type, referred to as *poor*, do not use such technologies. In our model, all countries rely on the same stock of primary resource supplied by a mining industry located in very few exporting countries that will not be considered in the further analysis. The demand for P differs between the two types of countries as rich countries have P-saturated soils while soils in poor countries are P-deficient.

Although our analysis does not capture all aspects of the P-cycle and abstracts from many important technological and economic details, our set-up captures the main features relevant for phosphorus use. We develop an analytically tractable model that gives general insights into the inter-regional and intertemporal P-allocation. Its solution may lead to a better understanding of the distributional issues in non-renewable resource use. This in turn could direct technology and support decision-making in P-resources management.

We find that developing countries benefit in the short and medium term from phosphorus recycling in industrialised countries but face stronger competition for the resource in the long-term. Future generations in both, rich and poor countries, benefit from recycling in the rich country.

The next section explains in some more detail the empirical evidence underlying the main assumptions of our model. Section 3 sets up the model. Section 4 presents the main results. In Section 5 we summarise the findings and draw some conclusions for phosphorus resource policies.

2. The empirical basis

Nutrient inputs to agriculture have always been limiting food production. Nutrients are removed from agricultural soils mostly through harvest and erosion. To maintain soil fertility the amounts removed need to be replenished in the soil. Contrary to nitrogen that can be fixed from an unlimited stock in the atmosphere, phosphorus (P), the next widely used macronutrient, can only be extracted from limited reserves of rock phosphate. Yet, rock phosphates are poorly soluble and, if processed, soluble phosphate becomes rapidly immobilised into insoluble forms upon its application (Smil, 2000). As a result, a large portion gets lost into waterways entering the longer route of the geological cycle. The largest P flow is carried through the rivers and leads to a high dispersion in the sediment on the ocean floors. The dissolved part represents the most diffuse state reached by phosphorus in the course of its complex flows (Blackwelder, 1916). Goeller and Weinberg (1976) claim that agriculture would be intolerably costly if society would have to rely on the low background P levels, even with a renewable energy source.

In the typical setting of developed countries with concentrated animal production, meat-based diets, large-scale sanitation and advanced wastewater treatment technologies, P-recycling is a feasible option. Phosphorus contained in excess manure or sewage sludge can be conserved and used employing the current recycling technologies and improved technologies are likely to become available in the future. Although this will not solve the global depletion problem ultimately, such technologies can generate a perfect substitute for rock phosphates which will contribute to maintaining agricultural productivity over a longer time span. An additional advantage of P recovery from urban waste is the protection surface waters.

On P-deficient soils the larger part of the applied nutrient is lost to the P-binding sites of the soil and becomes unavailable to plants. If more nutrients are removed from the soil through losses and harvest than replenished, nutrient mining results. This is a wide-spread phenomenon on many P-deficient soils in developing countries (Sheldrick et al., 2002). Deficiencies and negative balances of P in the arable soil impair agricultural productivities in various parts of the world in particular in Sub-Sahara Africa (Runge-Metzger, 1995). As agricultural soils are not saturated with nutrients, low soil fertility constrains productivity. Even if biotechnological measures, such as using genetically improved crops, are employed, their potential for higher productivities cannot be fully exploited when soils are depleted of plant nutrients (Sanchez, 2002). Soil fertility can be increased by successive fertilizer applications with some positive balance. This is a major driver of the current increase in P-fertilizer use observed in many developing countries.

The future availability of P resources is hard to forecast. This is due to the uncertainties in both, the size of the global resources of rock phosphate and the future P demand. Concerning the resource base, current estimates of their size vary widely. Although the estimates are burdened by uncertainties, reserves of rock phosphate are clearly limited. Phosphate reserves are concentrated in few regions; only four countries, United States, China, West Sahara, and Russia are supplying rock phosphate for about 72% of the P fertiliser produced (FAO, 2004). According to Klindworth (2000) markets for fertilizer products are global in scope due to the geographical concentration of the natural resources. This is certainly the case for P.

On the demand side, the historical development provides insights about how future demand will evolve. For fertilizers in general IFA/UNEP (1998) describes the evolution of demand as a 3-stages process. Each stage may take decades.

1. The introductory stage, where only few productive farmers use fertilizer.
2. The take-off stage, when the number of users and consumption grow rapidly.
3. The mature stage, where a majority of farmers use fertilizers at rates which do no longer grow.

In our model, we assume that the developed countries have reached the third stage. Environmental concerns will cause a decline in the demand for P fertilizers in Western Europe and possibly in North America. Developing countries, however, are generally in the first or second stage. IFA (2002) data reveal that in 1960 world fertilizer consumption of developing countries accounted for 12% of the world total. This increased to around 60% of a much larger total by 2001 indicating that some developing countries have entered the take-off phase. According to IFDC (1998) trends and projections also show that the increased need for agricultural intensification in Asia, Africa and Latin America will be the major source of expansion in demand for P-fertilizers in the first two or three decades of the 21st century. Nevertheless, many developing countries are still in the introductory period. Some regions, like Sub-Sahara Africa, face an annual loss of nutrients leading toward critical impoverishment (Smaling, 1993). These regions seem to need much more fertilizer input as the rate of depletion is especially high and increasing (Stoorvogel and Smaling, 1990) while per capita food production is declining (Van Straaten, 2006). In Ethiopia, soil fertility depletion in smallholder farms is one biophysical cause for declining per capita food production (Haileslassie et al., 2005). Pointing at the social and economic aspects affecting soil mining Koning and Smaling (2005) criticise agronomists' focus on purely technological solutions neglecting the environmental and social aspects. Koning and Smaling (2005) accentuate the dynamics of world market prices as a potential source of soil degradation in Africa. According to IFA/UNEP (1998) fertilizer imports account for an important share of spending of foreign exchange in African countries. Fertilizer subsidies seem to be one way of solving the problem. Yet, any policy advice on market interventions should be preceded by a clear understanding of the market and of long-term implications.[1]

The above trends for fertilizers in general also apply to P fertilizers. Developing and developed countries have markedly different problems concerning P. The former still have low P concentrations in their agricultural soils (IFA, 2005), whereas the latter are coping with the consequences of excessive use and environmental pollution. The reasons for increasing the use of P fertilizer in the developing countries can be summarised as

- P-deficient agricultural soils,
- population increase and increasing food demand,
- shifts in diet towards meat requiring more P fertilizer per unit of food energy.

By comparison, the reasons for the levelling-off of P fertilizer consumption in developed countries are

- P-saturated agricultural soils,
- stable population and food consumption patterns,
- environmental pollution.

This view of the differences between developing and developed countries is supported by the studies of nutrient balances for Japan and Kenya (Sheldrick et al., 2002). Other balances for Europe in the 1990ies showed an average annual surplus of P of around 12 kg P/ha, with the Netherlands having the highest surplus of around 57 kg P/ha (Sibbesen and Runge-Metzger, 1995). In Western Europe, due to environmental concerns, improved agricultural practice and improved P-levels in soils, the use of phosphorus fertiliser has been reduced over time from around 70 kg $\text{ha}^{-1}\,\text{yr}^{-1}$ in the 70ies to levels of 25–30 kg $\text{ha}^{-1}\,\text{yr}^{-1}$ in recent years (Pradt, 2003).

3. The model

We use a dynamic optimisation framework that determines price and extraction paths for a given stock of phosphorus resources. Our model builds on the seminal exhaustible resources model of Hotelling (1931); see also Neher (1990, chapter 4). The model is extended in three different ways. We introduce (*i*) two types of countries, rich and poor, with (*ii*) a kinked demand curve for rich countries reflecting P-saturated soils and (*iii*) recycling in the rich countries. We will develop the case with recycling as a general model and compare it to a reference scenario without recycling in order to study the effect of recycling on the distribution of the resource between the developed and the developing parts of the world over time.

In our setting with a competitive resource market for a non-renewable resource Hotelling's rule applies. In the equilibrium each mining firm is indifferent between conservation and extraction. Hence, the relative change in resource price equals the interest rate. Formally,

$$\frac{\dot{p}_t}{p_t} = r. \tag{1}$$

For simplicity we do not consider extraction costs. Each country maximises net benefits from the use of phosphorus, denoted by V. The objective function at each point in time is given by

$$V_t = B(x_t + y_t) - p_t x_t - C(x_t, y_t), \tag{2}$$

where benefits $B(x,y)$ are derived directly from imported phosphorus x and recycled phosphorus y. $C(x,y)$ denotes recycling costs. Prices are exogenous from the perspective of a single country. Imported and recycled P are considered to be perfect substitutes.

The first order condition of the maximisation of Eq. (2) gives

$$B_x - p - C_x = 0 \tag{3}$$

and

$$B_y - C_y = 0, \tag{4}$$

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[1] Grote et al. (2005) discuss international nutrient flows caused by trade in more detail. Their analysis, however, is confined to the aggregate of N, P and K fertilizers.

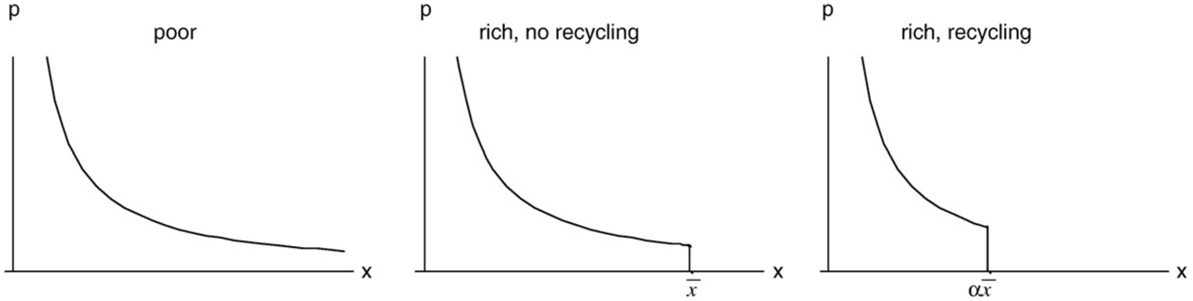

Fig. 1 – Demand functions.

where we skip the time index for notational convenience and partial derivatives are denoted by subscripts. As x and y are perfect substitutes we have $B_x = B_y$ and it follows that

$$C_y - C_x = p. \tag{5}$$

As it is difficult to make progress in the analysis on the level of general benefit and cost functions, we will from here on work with functional specifications. Concerning the recycling costs we adopt the simplest possible specification that captures the following key features of recycling: (i) recycling costs and marginal recycling costs are increasing in the recycling rate (and are zero for no recycling), (ii) full recycling is impossible, (iii) recycling costs are increasing in the amount recycled and (iv) for a given recycling rate unit costs are lower if phosphorus is recycled from a larger flow. The recycling rate is defined as $\rho \equiv y/(x+y)$ with $\rho \in (0,1)$; cf. Dasgupta and Heal (1979, p.212). To build a formal cost function $C(x,y)$ first consider costs as a function of the recycling rate, denoted by $\hat{C}(\rho)$. The first requirement can then be written as

$$\text{(i)} \quad \frac{d\,\hat{C}(\rho)}{d\rho} > 0, \quad \frac{d^2\,\hat{C}(\rho)}{d\rho^2} > 0 \quad \text{and} \quad \hat{C}(0) = 0.$$

As full recycling is never possible, it is plausible to assume that recycling cost would rise without limit as ρ approaches 1, i.e. if (almost) the entire flow is recycled and imports from the mine are a negligible part of the flow. Hence, we have

$$\text{(ii)} \quad \lim_{\rho \to 1} \hat{C}(\rho) = \infty.$$

A simple cost function that exhibits these properties is

$$\hat{C}(\rho) = \alpha \frac{\rho}{1-\rho}, \tag{6}$$

where $0 < \alpha < 1$ is scaling factor. We require $\alpha < 1$ to guarantee that recycling is worth while.[2] Substituting $y/(x+y)$ for ρ in Eq. (6) we obtain a cost function with arguments x and y:

$$C(x,y) = \alpha \frac{y}{x}. \tag{6$'$}$$

It is easy to check that requirements

$$\text{(iii)} \quad C_y > 0$$

and

(iv) if the flow $(x+y)$ is scaled up to $k(x+y)$ with $k>1$, then $C(kx, ky)/ky < C(x,y)/y$

also hold for the cost function (6′).

Next, we specify the benefits functions for a poor and a rich country (referred to by superscripts P and R) as follows:

$$B^P = \ln\left(x^P\right), \tag{7}$$

$$B^R = \min\left(\ln\left(x^R + y^R\right), \ln\bar{x}\right). \tag{8}$$

As P is an essential resource, marginal utility rises without limits as consumption approaches zero. In addition benefits of phosphorus application are limited to $\ln\bar{x}$ in rich countries as soils are P-saturated. This feature gives rise to a kinked demand curve for a rich country. Note that rich and poor countries are assumed to be identical in all other respects in order to focus the analysis on the key features of P use. With these specifications we obtain from Eq. (3) the following demand functions for the reference case without recycling (i.e. $y = 0$):

$$x^P = \frac{1}{p}, \tag{9}$$

and

$$x^R = \min\left(\frac{1}{p}, \bar{x}\right). \tag{10}$$

For the case with recycling in rich countries we have from Eqs. (5) and (6′)

$$p = \alpha\left(\frac{1}{x} + \frac{y}{x^2}\right). \tag{11}$$

From Eq. (4) and the specifications (6′) and (8) we obtain $\frac{1}{x+y} = \frac{\alpha}{x}$. Solving this for y gives

$$y = \left(\frac{1}{\alpha} - 1\right)x. \tag{12}$$

Substituting Eq. (12) into Eq. (11) gives $p = \frac{1}{x}$. Taking the upper bound of benefits into account, this holds as long as $x + y \leq \bar{x}$. Hence, demand is given by

$$x^R = \min\left(\frac{1}{p}, \alpha\bar{x}\right). \tag{13}$$

The demand functions are depicted in Fig. 1. It is interesting to note that if high resource prices prevail, demand is not reduced

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[2] If costs are scaled up such that $\alpha \geq 1$, we obtain the corner solution $y = 0$. This can be seen from Eq. (12) below.

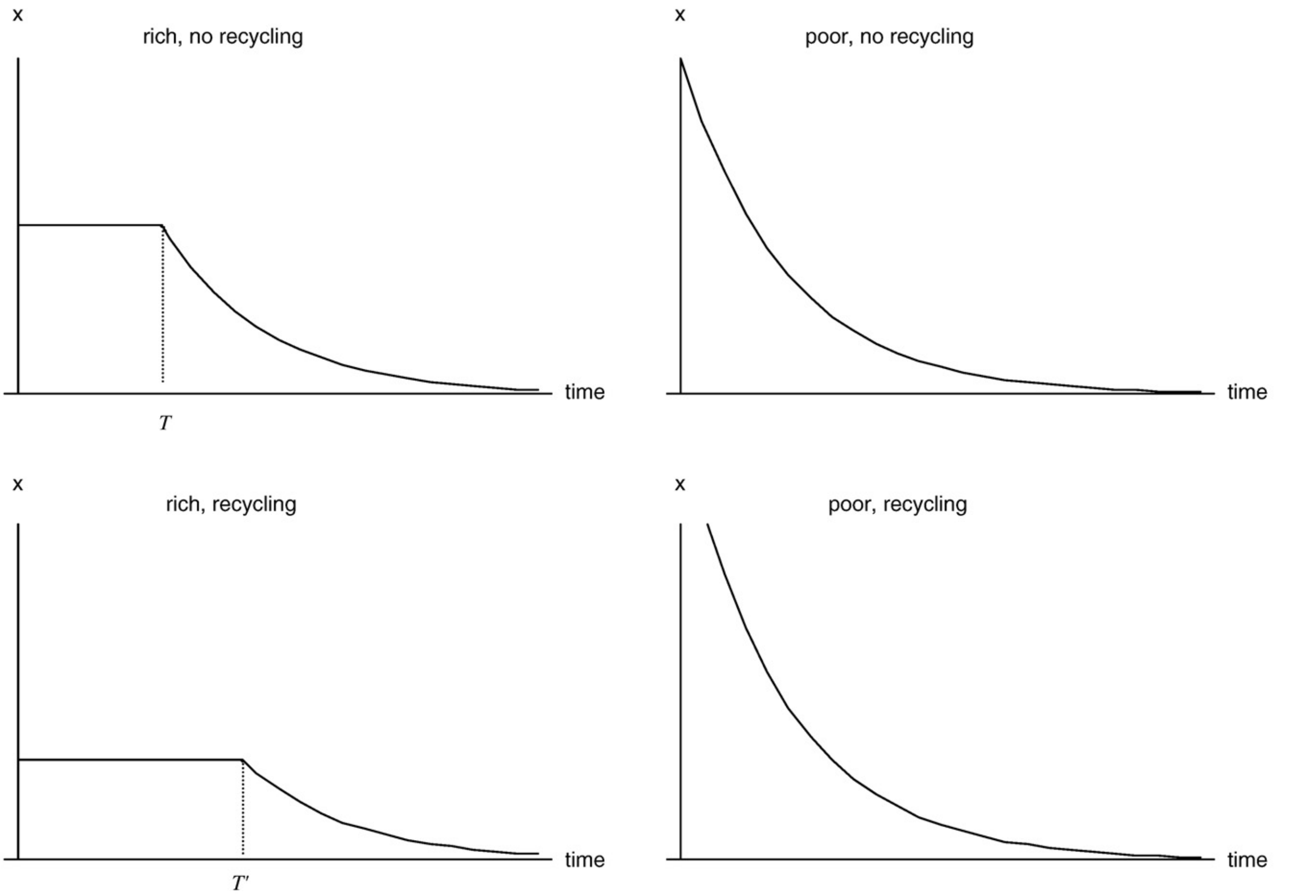

Fig. 2 – Consumption paths of rich and poor countries without recycling and with recycling in rich countries.

through recycling. The economic reason is that recycling increases the marginal productivity of imported resources. The effect of more phosphorus being available through recycling is counterbalanced by a higher willingness to pay for imported resources. The demand curve is only affected by a satiation effect. Its kink shifts from $\bar{x}$ to a lower level $\alpha\bar{x}$ (see Fig. 1).

4. Model results

We first derive results for the reference case without recycling. Notice that the kinked demand curve of a rich country gives rise to a kink in the extraction path. We can distinguish two phases. In phase 1 the price is sufficiently low. Hence, country *R*'s imports are limited to $\bar{x}$. From Eq. (10) we know that the kink is reached if $\frac{1}{p}=\bar{x}$. Hence, at the time the kink is reached, denoted T, we have $p^T=\frac{1}{\bar{x}}$. Using Hotelling's rule we have $p_T=p_0e^{rT}$ Solving for *T* gives

$$T=\frac{1}{r}\ln\frac{1}{p_0\bar{x}}. \tag{14}$$

Assuming that we have *n* rich and *m* poor countries, the total extraction (sales) in this phase is given by

$$\int_0^T\left(\frac{m}{p_0e^{rt}}+n\bar{x}\right)dt. \tag{15}$$

In the second phase, for all $t>T$, the price is sufficiently high such that $\frac{1}{p}<\bar{x}$. Total extraction in this phase is given by

$$\int_T^\infty\frac{n+m}{p_0e^{rt}}dt. \tag{16}$$

For a given stock of resources the initial price p_0 is implicitly determined by the resource constraint which is obtained by combining Eq. (15) and Eq. (16).

$$S_0=\int_0^T\left(\frac{m}{p_0e^{rt}}+n\bar{x}\right)dt+\int_T^\infty\frac{n+m}{p_0e^{rt}}dt, \tag{17}$$

where S_0 denotes the total initial stock of rock phosphate.

With recycling the kink in the demand curve of the rich country shifts from $\bar{x}$ to a lower level $\alpha\bar{x}$, $0<\alpha<1$; see Eq. (13). This has two main effects in phase 1. First, the imports of rich countries are reduced. This reduces the initial price p_0 to $p_0'<p_0$ and, hence, imports of poor countries will be larger. Second, the length of the phase where rich countries have saturated soils is extended. This can be seen when $\bar{x}$ is replaced by $\alpha\bar{x}$ in Eq. (14). The time when the kink is reached with recycling will be

$$T'=\frac{1}{r}\ln\frac{1}{p_0'\alpha\bar{x}}. \tag{14′}$$

In Fig. 2 we display the consumption paths for rock phosphates for rich (left panels) and poor countries (right panels). Consumption paths are displayed for the reference case without recycling (upper panels) and for the scenario where rich countries implement P-recycling (lower panels). With a lower initial price, due to recycling, the poor countries will always use more of the resource as compared to the reference case. The rich countries use less in the early phase but maintain this level for longer — keeping soils P-saturated. This implies that at a later stage more P can be extracted from the mine and the inevitable soil mining will be delayed.

To examine welfare effects, note that developing countries gain at each point in time because they buy at a reduced price $p'_t < p_t$ and increase their consumption to $x'_t > x_t$. The gain in consumer surplus is given by

$$\int_0^{x'_t} \frac{1}{p} dx - p'_t x'_t - \int_0^{x_t} \frac{1}{p} dx + p_t x_t, \tag{18}$$

using the demand function (9). The first two terms in Eq. (18) are benefits and costs for the case of recycling; the third and fourth term are benefits and costs for the reference case. A part of that gain, $(p'_t - p_t)x_t$, stems from a loss of producers' rents. To examine the welfare effects of developed countries we need to distinguish three phases. At any point in time $t < T$ soils are kept saturated. The welfare gains from recycling stem from cost reductions which amount to $p_t\bar{x} - p'_t\alpha\bar{x} - (1-\alpha)$. The first term is the reference case expenditure; the second term is the expenditure for rock phosphate with recycling; the third term is the cost of recycling an amount $(1-\alpha)\bar{x}$. In a second phase, when $T \leq t < T'$, there are cost reductions and additional benefits due to maintaining P-saturation of soils. The welfare effect is

$$\int_0^{\bar{x}} \frac{1}{p} dx - p'_t\alpha\bar{x} - (1-\alpha) - \int_0^{x_t} \frac{1}{p} dx + p_t x_t. \tag{19}$$

In Eq. (19) the first term captures benefits of P use; the second and third term are costs for rock phosphate and recycling, respectively; the fourth and fifth term are benefits and costs for the reference case. Finally, in a third phase, when $T' \leq t$, developed countries' welfare gains of recycling are the same as the gains for developing countries as described above, see Eq. (18).

Fig. 3 shows a comparison of paths for total extractions with and without recycling. We observe two cross-overs that demarcate three phases. In the first phase, the near future, recycling has an adverse effect on total extraction. Extraction is larger with recycling than without. Recycling lowers equilibrium prices which triggers an increase of rock phosphate imports in poor countries. This effect overcompensates the reduced demand in rich countries due to recycling and P saturation of soils. Hence, the near future is characterised by a rebound effect: improved efficiency in P use triggers larger resource use. Over time rising prices reduce consumption in poor countries while consumption is maintained in rich countries until price reaches the kink of the demand curve. As recycling reduces demand for rock phosphate in developed countries, a smaller share of the market is inelastic compared to the reference case without recycling. The response to a rising resource price is, therefore, more pronounced and the extraction path is steeper with recycling than without. This generates the first cross over. The second phase, the medium future, exhibits the expected characteristics: recycling does indeed reduce extraction and saves P resources for the far future. In the reference case developed countries consume a fixed amount of rock phosphate $\bar{x}$ until time T. After that the market becomes more elastic, quantities are reduced as price rises and the extraction path kinks and becomes steeper. This leads to the second cross-over. In the third phase, the far future, we have higher consumption with recycling than without (see Fig. 3).

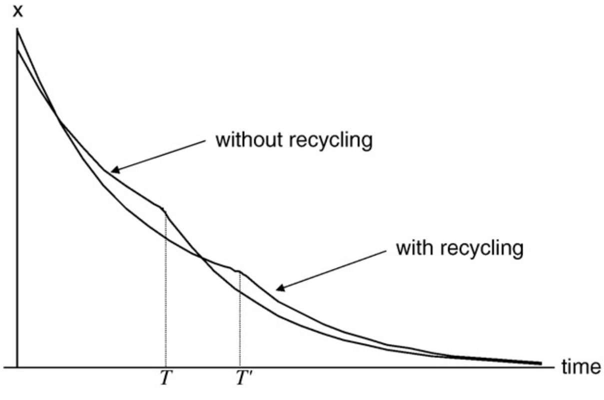

Fig. 3 – Total consumption.

5. Summary and concluding remarks

Some important features distinguish P from other non-renewable resources. It differs from most metals because it is non-substitutable in its main use and it differs from fossil fuels because it is not used-up by consumption but can be recovered to some extent. We provide a model analysis of the effect of recycling of phosphates from wastes. Although recycling will also have positive effects of pollution reduction we focus on the resource input side of the phosphorus allocation problem where recycled phosphate is a substitute for rock phosphate from depletable mines.

Summarising our findings we can state three main effects. First, poor countries will increase their imports due to P recycling in developed countries at all times. They benefit from a lower price path. Second, total resource extraction is increased in the short term, a rebound effect, and reduced in the medium term. The reduction effect is stronger and thus more P resources are available for future generations. In the long-run recycling in rich countries does not imply a higher share of resources for poor countries. As soon as prices rise to a level where soil mining starts in rich countries, that is when fertilizer application falls short of full replenishment, poor countries will face full competition. Recycling has two effects working in opposite directions. On the one hand, recycling delivers a substitute for rock phosphates which reduces demand. On the other hand, recycling increases P-use efficiency in developed countries which drives up demand. These results have been obtained extending Hotelling's extraction model to capture the impacts of differences in demand and the impacts of recycling. For a proper interpretation of results it is important to mention three limitations of our model. First, as described in Section 2, phosphorus resources are concentrated in few countries. However, our model does not capture the effect of market power on the price path. Second, we neglect population growth. Rather than assuming a time-invariant demand function, growing demand in developing countries is a more appropriate assumption. Third, the increased depletion of rock phosphates in the short term will largely be used to build up P stocks in agricultural soils in developing countries. Our model does not fully capture the effect of P stocks on productivity of agricultural soils.

The development of technologies for recycling of phosphorus is an inevitable consequence of the non-renewability of rock phosphate and the non-substitutability of phosphates in agricultural production. The distributional effects of recycling that we consider are linked to regional development aspects. The challenge for the future is to develop P-recycling technologies applicable in rich and in poor countries.

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