Chemosphere 84 (2011) 798–805

Contents lists available at ScienceDirect

Chemosphere

journal homepage: www.elsevier.com/locate/chemosphere

Modeling biogeochemical processes of phosphorus for global food supply

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ARTICLE INFO

Article history:
Received 5 October 2010
Received in revised form 1 February 2011
Accepted 18 February 2011
Available online 3 April 2011

Keywords:
Probabilistic modeling
Phosphorus bioavailability
Global cycle
Food supply

ABSTRACT

Harvests of crops, their trade and consumption, soil erosion, fertilization and recycling of organic waste generate fluxes of phosphorus in and out of the soil that continuously change the worldwide spatial distribution of total phosphorus in arable soils. Furthermore, due to variability in the properties of the virgin soils and the different histories of agricultural practices, on a planetary scale, the distribution of total soil phosphorus is very heterogeneous. There are two key relationships that determine how this distribution and its change over time affect crop yields. One is the relationship between total soil phosphorus and bioavailable soil phosphorus and the second is the relationship between bioavailable soil phosphorus and yields. Both of these depend on environmental variables such as soil properties and climate. We propose a model in which these relationships are described probabilistically and integrated with the dynamic feedbacks of *P* cycling in the human ecosystem. The model we propose is a first step towards evaluating the large-scale effects of different nutrient management scenarios. One application of particular interest is to evaluate the vulnerability of different regions to an increased scarcity in *P* mineral fertilizers. Another is to evaluate different regions' deficiency in total soil phosphorus compared with the level at which they could sustain their maximum potential yield without external mineral inputs of phosphorus but solely by recycling organic matter to close the nutrient cycle.

1. Introduction

Despite its vital importance to all life forms and the global scale of its flows, no biogeochemical cycle model exists for phosphorus (*P*) to quantify the temporal and spatial patterns of its distribution on Earth. Yet, due to the small size of the known *P*-bearing rock deposits (Jasinski, 2009), concerns are rising about future provision of mineral *P* fertilizer to agro-ecosystems. At the same time as these concerns are voiced, tens of millions of tons of *P* harmfully make their way to aquatic systems annually (Liu et al., 2004). While in most ecosystems, *P* cycles several hundred times from the soil to the biomass to the zoomass back to the soil before finding its way to the aquatic systems (Smil, 2000), most human-managed systems are much less efficient as *P* cycles rarely more than once. *P* is a constitutive element of basic cellular processes and structures and as such is a non-substitutable ingredient to plant growth. Finally, *P* is distributed via global markets, traded in the form of food and mineral, the latter being supplied only by a handful of countries which hold more than ninety percent of the known world terrestrial *P*-bearing rock reserves (Cordell et al., 2009). In a precautionary perspective, we should investigate the vulnerabilities for global food production that are associated with the usage patterns sketched above. We should also examine the impact on food production, cost and pollution of different scenarios of *P* supply – from the current extractive model to a potential closed cycle. To achieve this, we need a quantitative understanding of *P* stores and flows and their dynamics on a global scale.

As a first step towards quantifying the *P* cycle, the objective of this paper is to present a model of *P* flows through arable soils and the resulting effect on crop yields. This model is based on substance-flow analyses proposed by other authors (e.g. Liu et al., 2004) but it is dynamic. We seek to develop a simple probabilistic formulation that can be applied at different scales. We argue for a simple solution to the scaling of the complex dynamics of *P* cycling in soils, usually handled by deterministic models that cannot easily be scaled because of the site-specific parameterization needed to implement them (e.g. Jones et al., 1984). One application of our model will be to simulate the evolution of food production when suppressing the inflow of mineral *P* fertilizer, as a way to evaluate our level of dependence on *P*-bearing rocks. The model will have wider applications: for example, to quantify the amount of *P* fertilizer necessary to transition to a long-term steady-state closed-loop cycle. This paper may contribute to methodologies for integrating LCA and biogeochemistry for the successful management of biogeochemical-cycles.

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doi:10.1016/j.chemosphere.2011.02.039

2. Modeling the *P* cycle

2.1. Formalizing how P cycles through the "human ecosystem"

Evaluating the impact on crop yields is one way to translate different states of the *P* cycle in terms of units that matter to society. Correspondingly, we built a simple model of *P* cycling whose output variable is total food production (Fig. 1). The boundaries drawn in Fig. 1 represent a particular agricultural region, typically composed of both cropland and grassland. Although Fig. 1 represents a large number of pathways, the dynamics can be summarized as follows:

$$\frac{dy}{dt} = \frac{dy}{dP_a}\frac{dP_a}{dP_T}\frac{dP_T}{dt} \tag{1}$$

where y is the yearly yield per hectare, P_T is the total concentration of all *P* compounds in the soil and P_a (plant-available *P*) is the concentration of *P* that is loosely bound to the soil and can enter the soil solution to be taken up by roots.

In Eq. (1), dP_T/dt represents the balance of *P* flows in and out of the soil. It is composed of: (1) x_{er}, the out-flux from the land to the river network, principally due to soil erosion but influenced by human activities; (2) out-fluxes of *P* contained in harvested crops $(x_{y_c}), (x_{y_f})$ and grass (x_{y_g}); 3) in-flux of *P* from the application of *P* fertilizers (null if we consider a scenario of shortage) and the application of manure (x_{ma}), crop residues (x_{re}), and human waste (x_{hw}). Clearly, these flows, associated with our management of the cycle, affect P_T, the total stock of *P* in soils. Crop yields, on the other hand, are affected by P_a, the fraction of soil *P* that is bioavailable. Indeed, the term dy/dP_a can be modeled by what agronomists call the yield response function of a crop, which indicates as a function of P_a how much a plant can achieve of its maximum potential yield. Hence, to understand how the large-scale fluxes of *P* through society and across the landscape affect food production, one needs to understand the relationship between P_a and P_T.

In the next two sections of this paper, we present our main contribution to the quantitative understanding of the cycle depicted in Fig. 1, that is, to propose a way to model the term dP_a/dP_T such that it can be integrated with the balance of flows dP_T/dt and the crop responses dy/dP_a.

2.2. Probabilistic modeling of the bioavailability of P in the landscape

From the soluble or loosely bound state (P_a), *P* is taken up by the biomass but also reacts reversibly with a wide range of minerals. As a result, *P* is present in soils in myriads of chemical compounds, which can broadly be categorized in three classes: organic compounds, mineral precipitates and surface complexes with metal oxides and clays (Frossard et al., 2000).

The relative importance of the three main classes of compounds (precipitates, metal oxides and organics) varies with some degree of predictability with the types and properties of soils (Sharpley and Cole, 1987). This observation explains the following key patterns (examples can be found in Syers et al., 2008). First, some soils in the northern latitudes that have been fertilized for long periods of time can be left unfertilized for decades without showing any change in the levels of P_a: the *P* supplied as fertilizer has been stored in stable forms and is being re-supplied over time to the plants in the absence of new fertilizer inputs (for e.g., Otabbong et al., 1997). Second, and in contrast, on highly weathered soils in the tropics, yields may decline very rapidly if fresh *P* in the form of mineral fertilizer is not applied on a regular basis (for e.g., Beck

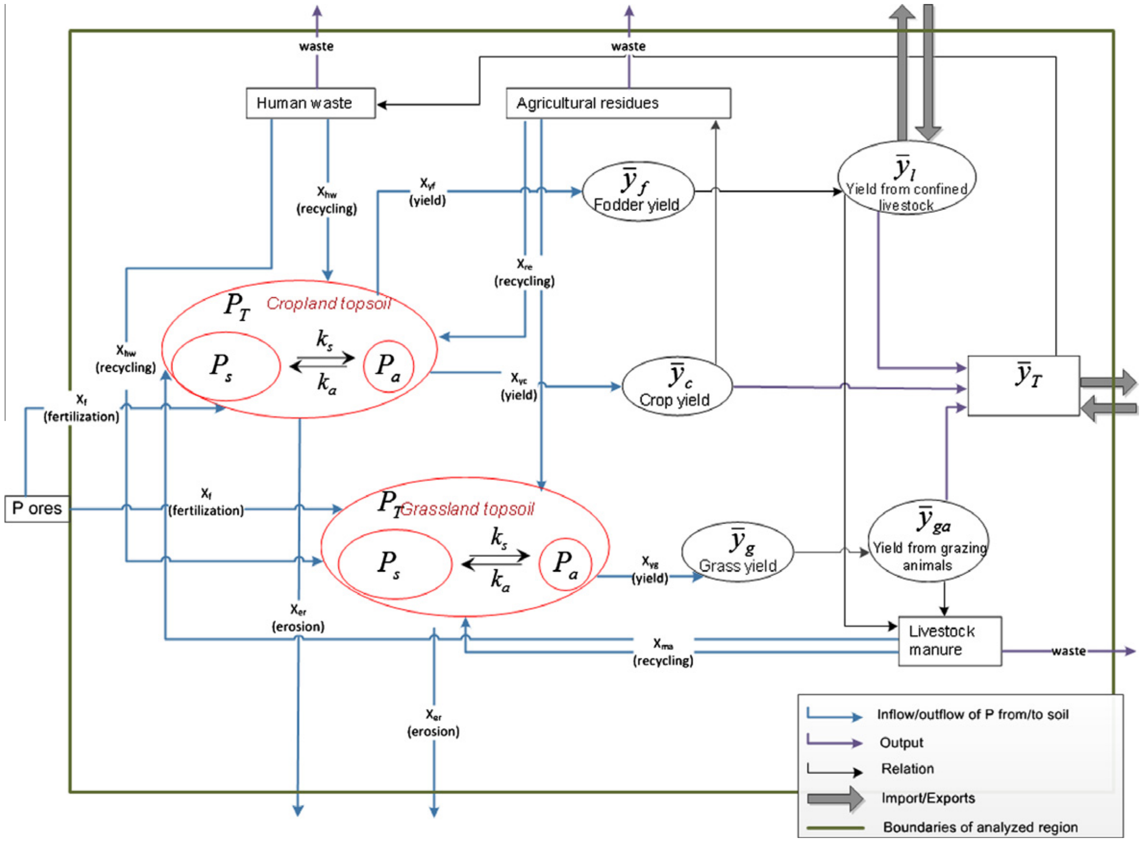

Fig. 1. Phosphorus cycling through the human ecosystem. A region composed of grassland and cropland. Food production consists of crops, confined livestock fed by fodder and grazing animals fed by grass. $\bar{y}_\bullet$ signifies the total yield of crops, animals etc. and $x_\bullet$ stand for the different fluxes (e.g. x_{hw} for Human waste) in or out of the pool of P_T. The terms P_s, P_a, k_s and k_a are elucidated in the article.