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Future agricultural phosphorus demand according to the shared socioeconomic pathways

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ABSTRACT

A spatially explicit, two-pool soil phosphorus (P) model was used to analyze cropland P dynamics and fertilizer demand based on future crop production as projected in the shared socioeconomic pathways (SSPs). The model was initialized with historical data on P inputs and uptake, which governed the soil P accumulation up to present day. In contrast to existing scenario studies, the model accounts for both soil characteristics relevant to P retention and changing land use. At the global scale, crop uptake and the fraction of the applied P fertilizer that is directly taken up by plant roots govern the P quantities present in the soil. Despite the differences in the storylines among the SSPs, the quantitative implementation results in estimates for crop production and P inputs that are quite similar, which contrasts with the stark divergence in terms of population and incomes. In addition to global fertilizer P inputs in croplands increasing from 14.5 Tg P yr^{-1} in 2005 to 22–27 Tg P yr^{-1} in 2050, this study also estimates that 4–12 Tg P yr^{-1} would be needed in 2050 in global intensively managed grasslands to maintain fertility. Our new model approach can pinpoint the contribution of area expansion and crop yield improvement toward the total production, whereby the latter is shown to contribute 100% to 69%, depending on the scenario.

1. Introduction

Phosphorus (P) is an essential nutrient for living organisms and has played an important role in agriculture since the start of the 20th century (Koning et al., 2008; Sattari et al., 2012). Early (pre-20th century) P applications in agriculture depended on manure and guano, bone meal, and urban waste (Beaton, 2006). Limited nitrogen (N) and P availability were key factors in the low crop yields. During the post-war industrial and population boom (1950–1970), the expansion of P mining allowed for the rapid development of mineral fertilizers, which took over as the leading agricultural P input in industrialized countries (Cordell et al., 2009). In the 1970s and 1980s, disproportionate fertilizer and manure P use in industrialized countries led to low P use efficiency, and consequently, large amounts of surplus P were retained as residual P in soils (Syers et al., 2008). After this accumulation phase, farmers in many industrialized countries have been able to increase their P use efficiency as a result of reduced input, mining of the accumulated residual soil P reserves, improved agricultural management, and enhanced crop uptake (Sattari et al., 2012); in many cases even increasing crop yields (Bouwman et al., 2017). In contrast, China and India are currently in the phase of increasing P surpluses and decreasing nutrient use efficiencies, similar to the industrial countries in the 1970s and 1980s. Many developing countries are in the early phases of agricultural development with minimal P application rates, which often coincide with low crop yields (Bouwman et al., 2017).

Future P usage will play an important role in sustaining food production for the projected world population growth from 7.3 in 2015 to 9.7 billion inhabitants in 2050 (medium variant of UN, 2016). Nevertheless, phosphate rock is a finite resource and the high-quality and high-grade phosphate rock reserves are decreasing, although the estimates are quite variable. Based on a Hubbert linearization, peak in P annual production has been estimated to have taken place in 1989 (Déry and Anderson, 2007). Adapting the Hubbert curve to account for all depleted and current reserves, peak P production was pushed to 2033 (Cordell et al., 2009). Another assessment, based on consumption and production models that included future changes in regional P production costs, projected a 20–60% resource depletion by 2100 (van Vuuren et al., 2010). Furthermore, based on revised definitions for reserves and resources, additional data that included a second production peak in 2008, and updated reserve estimates for Morocco, Van Kauwenbergh (2010) argued that P for fertilizer production would be available for 300–400 years. It is also important to note that, despite the

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importance of P as a resource, the fate of P surpluses in soils has been largely ignored in agricultural modeling studies (e.g. Bouwman et al., 2009, 2013; MacDonald et al., 2011).

Recently, Sattari et al. (2012; 2016) adapted the Dynamic Phosphorus Pool Simulator (DPPS) to capture the effects of residual P and even extrapolate the effects of increased P loads in future cropland production at the country scale. Zhang et al. (2017) further expanded DPPS to simulate the soil P stocks and crop uptake globally using a spatially explicit grid (0.5 by 0.5° resolution) during the 20th century, taking into account historical changes in cropland area and soil P retention potential. In our current study, we couple the spatially explicit version of DPPS with the Integrated Model to Assess the Global Environment (IMAGE; Stehfest et al., 2014). This IMAGE-DPPS model is used to evaluate the future demand for P in agriculture according to the five shared socioeconomic pathways (SSPs; van Vuuren et al., 2017). The SSPs represent scenarios developed to study the impact of future global change (population dynamics, economic growth, and consequent food and energy production, climate change, land use changes) and thus the main factors controlling future agricultural nutrient cycles.

2. Methods

2.1. Model and data

The spatially explicit (0.5 × 0.5°), yearly DPPS model (Fig. 1a) was recently described in Zhang et al. (2017). DPPS considers natural or unintentional inputs to the soil and how they affect the labile (*LP*) and stabile (*SP*) phosphorus pools. *LP* comprises both organic and inorganic P forms that can more or less readily replenish P taken up by plant roots (Schachtman et al., 1998). *SP* represents forms of P bound to soil minerals and organic matter that are not directly available to plants. Inputs to *LP* consist of weathering (*W*, $\mathrm{kg\,P\,ha^{-1}\,yr^{-1}}$) and litter (*L*, $\mathrm{kg\,P\,ha^{-1}\,yr^{-1}}$). Inputs to *SP* consist of atmospheric deposition (*D*, $\mathrm{kg\,P\,ha^{-1}\,yr^{-1}}$), which enters as soil dust. Soil formation (*H*) is also a natural input for both *LP* and *SP* and is taken into account following Zhang et al. (2017). Anthropogenic P inputs include application of mineral P fertilizer (*S*, $\mathrm{kg\,P\,ha^{-1}\,yr^{-1}}$) and animal manure spreading (*M*, $\mathrm{kg\,Pha^{-1}\,yr^{-1}}$). In contrast to Zhang et al. (2017), here part of fertilizer and manure inputs enter the *LP* (γ and ε, respectively) and another part is channeled toward *SP* (1−γ and 1−ε, respectively). Furthermore, a fraction is directly taken up by plant roots (1−σ= 20% for fertilizer, 1−η= 10% for manure) and the remainder is available and becomes part of *LP* (σ= 80% for fertilizer and η= 90% for manure).

The rate of change of *LP* and *SP* ($\mathrm{kg\ P\ ha^{-1}\ yr^{-1}}$) is calculated as follows:

$$\frac{\partial_{LP}}{\partial_t} = \frac{SP}{\mu_{SL}} - \frac{LP}{\mu_{LS}} + W + \sigma\gamma S + \eta\varepsilon M + H_{LP} + L - Q_{LP} - U \tag{1}$$

$$\frac{\partial_{SP}}{\partial_t} = \frac{LP}{\mu_{LS}} - \frac{SP}{\mu_{SL}} + (1-\gamma)\sigma S + (1-\varepsilon)\eta M + D + H_{SP} - Q_{SP} \tag{2}$$

where the variables μ_{LS} and μ_{SL} are transfer times (years) between *LP* to *SP* and *SP* to *LP*, respectively.

P outflows from the soil system include P withdrawal from *LP* by crops (*U*, $\mathrm{kg\,P\,ha^{-1}\,yr^{-1}}$) and runoff (including erosion, see Beusen et al., 2015) from both *LP* and *SP* (*Q*, $\mathrm{kg\,P\,ha^{-1}\,yr^{-1}}$). The model assumes that only a fraction (f_{av}) of *LP* is directly available for P uptake (*U*), which uses Michaelis-Menten kinetics (after Nijland et al., 2008) as follows:

$$U = \frac{U_{\max} f_{av} LP}{\frac{c\,U_{\max}}{I} + f_{av} LP} + (1-\sigma)\mathrm{S} + (1-\eta)M \tag{3}$$

where $U_{\max}$ ($\mathrm{kg\ P\ ha^{-1}yr^{-1}}$) is the maximum P uptake, and *I* is the initial recovery fraction (no dimension), which is the initial slope of the P response curve presented (Batjes, 2011) for all soil types distinguished in the legend of the FAO-Unesco soil map of the world (FAO-UNESCO, 1974). *c* is a constant to obtain the *AP* for which uptake is 0.5 times $U_{\max}$ (no dimension; $c = 0.5$). In contrast to Zhang et al. (2017), here we use the mid-range values of *I* (Batjes, 2011) and $U_{\max}$ is held constant with a value of 500 $\mathrm{kg\,P\,ha^{-1}\,yr^{-1}}$. The calculation of the area-weighted value of *I* for each grid cell is based on the sub-grid distribution of soil classes.

For each crop area within a grid cell at a given time, the model consists of thee equations (Eqs. (1)–(3)) and three unknowns (*LP*, *SP*, and either f_{av} for historical mode or *S* for scenario mode, Fig. 1b). Eqs. (1) and (2) are implicitly integrated and solved simultaneously with Eq. (3) to calculate these three variables. The solution is obtained by minimizing the difference between the measured (imposed) uptake and the simulated uptake. The system of equations may not converge due to insufficient *LP* in the soil to satisfy the uptake demand. In this case the entire *LP* pool is channeled toward uptake and a slight underestimation in the modelled uptake may be introduced at that year. In historical mode, the unknown f_{av} is allowed to vary between a minimum value of 0 and a maximum value of 1. In scenario mode, f_{av} becomes a parameterized value that varies according to the SSP storyline, with a minimum value of 0.05 for each age-pool and a maximum value of 1.

In historical mode, each cell is initialized in 1900 with *LP* and *SP* from the global gridded soil P inventory (Yang et al., 2013), representing the pre-industrial conditions. Thus the P availability may increase or decrease, depending on the pool sizes.

For scenario mode, IMAGE-DPPS follows a tight coupling with the IMAGE model, which uses data on crop and livestock production and trade by the food and agriculture system model MAGNET (Woltjer and Kuiper, 2014). Calculated *LP* and *SP* pools and f_{av} based on the historical simulation period from 1900 to 2005 (the base year of IMAGE) provide the starting point for the scenario simulations from 2006 to 2050. Using spatially explicit land use and crop P uptake (*U*) distributions generated by the IMAGE model (van Vuuren et al., 2017), the future P fertilizer (*S*) requirements can be estimated for each SSP. Note that the spatial distribution of future gridded *U* is based on the 2005 gridded spatial distribution for each country. In grid cells where cropland expansion occurs, natural soil (without fertilizer history) with initial P pools (Yang et al., 2013) is added. For grid cells with land abandonment (arable land to natural land), IMAGE-DPPS assumes a 30 year period for abandoned land to revert to natural conditions (e.g. Yang et al., 2013), and in this period the P in litter and uptake increase linearly with time from zero to the natural flux (in which uptake equals litterfall). Further details on the data sources are depicted in the supplementary materials.

2.2. Scenarios

The various scenarios are implemented to contrast future socioeconomic behavior and their impact on both resource use and the health of the environment. The five SSP scenarios (Table 1) describe future socioeconomic behavior according to different adaptation and mitigation challenges. Projections for all scenarios were taken from IMAGE until the year 2050. SSP2 represents the current tendency; that is, the middle-of-the-road scenario that uses the baseline technical agricultural trends for crop yields and livestock productivity from the FAO Agriculture Towards 2050 projection (Alexandratos and Bruinsma, 2012). SSP3 (fragmentation) represents the scenario with the highest mitigation and adaptation challenges. It has the largest population increase (up to 10 billion by 2050) and cropland expansion (21% increase from 2010 to 2050). Furthermore, GDP and average crop yield in 2050 become the lowest among all the scenarios. SSP4 (inequality) is the scenario where developed countries improve their socioeconomic and environmental outlook whilst developing countries follow a more fragmented path. This scenario thus has high adaptation challenges with countries increasingly diverging in their sustainability practices. SSP5 (conventional development) assumes a world where fossil fuels