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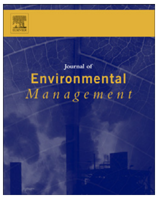

Research article

Quantitative evaluation of legacy phosphorus and its spatial distribution

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ABSTRACT

A phosphorus resource crisis threatens the security of global crop production, especially in developing countries like China and Brazil. Legacy phosphorus (legacy-P), which is left behind in agricultural soil by over-fertilization, can help address this issue as a new resource in the soil phosphorus pool. However, issues involved with calculating and defining the spatial distribution of legacy-P hinder its future utilization. To resolve these issues, this study applied remote sensing and ecohydrological modeling to precisely quantify legacy-P and define its spatial distribution in China's Sanjiang Plain from 2000 to 2014. The total legacy-P in the study area was calculated as 579,090 t with an annual average of 38,600 t; this comprises 51.83% of the phosphorus fertilizer applied annually. From 2000 to 2014, the annual amount of legacy-P increased by more than 3.42-fold, equivalent to a 2460-ton increase each year. The spatial distribution of legacy-P showed heterogeneity and agglomeration in this area, with peaks in cultivated land experiencing long-term agricultural development. This study supplies a new approach to finding legacy-P in soil as a precondition for future utilization. Once its spatial distribution is known, legacy-P can be better utilized in agriculture to help alleviate the phosphorus resource crisis.

1. Introduction

A global phosphorus (P) resource crisis has been gaining increasing attention. Although peak global phosphorus production is predicted to occur in the year 2030, global phosphorus reserves may be depleted in the next 50–100 years (Elser and Bennett, 2011). This phosphorus resource crisis is due to disequilibrium in global geographical distribution, increased artificial phosphorus fertilizer use, and phosphorus loss from agriculture and soil erosion. Worldwide phosphorus reserves are estimated at 6.7 billion t; global mining production in 2013 was 0.22 billion t (Schoumans et al., 2015). Three countries control more than 85% of known global phosphorus reserves: Morocco, China, and the United States (Elser and Bennett, 2011; Schoumans et al., 2015). Over 80% of the world's phosphate mined annually is used for manufacturing fertilizer (Withers et al., 2014; Scholz et al., 2015). China and Brazil consume large amounts of phosphorous as the two largest developing countries; China was responsible for 30% of global phosphorus fertilizer use in 2010 and Brazil imported 51% of its phosphate demand the same year (Sattari et al., 2014; Rodrigues et al., 2016). Unfortunately, 2.1–3.9 Tg of organic phosphorus and 12.5–22.5 Tg of inorganic phosphorus are permanently lost from terrestrial ecosystems annually (Quinton et al., 2010). *To resolve this crisis, more phosphorus resources urgently need to be made available in the soil phosphorus pool.*

Terrestrial legacy phosphorus (legacy-P) is an important phosphorus resource. Legacy-P is the phosphorus remaining in the soil from prior land management activities that builds up to levels exceeding crop requirements, consequently modifying the connectivity between terrestrial phosphorus and fluvial transport (Sharpley et al., 2013). Previous research indicates that inorganic aluminum phosphate (Al-P) and iron phosphate (Fe-P) are the primary components of legacy-P in soil (Liu et al., 2014; Rodrigues et al., 2016). For example, inorganic Al-P and Fe-P comprised about

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15.4% and 15.0%, respectively, of the total phosphorus in a Canadian agricultural field site from 1967 to 2010 (Liu et al., 2014). Phosphorus has strong adsorptivity, meaning that it accumulates easily in the soil, but also that it is not easily used by plants. The agricultural utilization efficiency of phosphorus fertilizer is lower than 20% globally and most phosphorus fertilizers are lost via runoff and soil erosion (Sharpley et al., 2015). Thus external sources of phosphorus input to agricultural soil drives legacy-P production. From 1960 to 1990, European application of phosphorus fertilizer increased steadily, consuming half the annual global use. In Asia, phosphorus fertilizer consumption has been increasing rapidly since the early 1980s and now accounts for over 50% of the annual global use (Schoumans et al., 2015). In South America, the average application of phosphorus fertilizer in Brazil has been increasing by 5% per year (Rodrigues et al., 2016). Continuous application of artificial phosphorus fertilizer increases soil legacy-P; for example U.K. soils contain 4–10 million t of legacy-P (Withers et al., 2014). In summary, *substantial legacy-P is currently present in global soils, especially in agricultural areas*.

There are three general methods used to study terrestrial legacy-P. The first is to use a simple statistical model by combining long-term agricultural management data (e.g., fertilizer use, crop production, and cultivated land area) and material balance arithmetic (Schoumans et al., 2015). The second method is the phosphorus life cycle method, which involves recording and describing the life cycle of soil phosphorus from artificial fertilizer, then applying concise arithmetic to calculate legacy-P in soil (Sattari et al., 2012; Jiang and Yuan, 2015). The third method is the soil chemistry method, in which legacy-P is directly measured (Liu et al., 2014; Rodrigues et al., 2016). However, the first method is less precise due to an oversimplification of the phosphorus cycle, while the second and third methods cannot derive accurate quantities and spatial distributions of soil legacy-P. None of the three methods can properly define the spatial-temporal variations of terrestrial legacy-P because they fail to describe the soil phosphorus cycle accurately enough, particularly within soils and plants.

Ecohydrological modeling and remote sensing can play leading roles in addressing these issues with terrestrial legacy-P studies. Ecohydrological modeling (e.g., the SWAT or EcoHAT-P models) simulates the terrestrial phosphorus cycle in soils and plants, including calculating the soil phosphorus concentrations, the content that plants absorb, and the amount lost to surface runoff and soil erosion (Liu et al., 2009; Neitsch et al., 2011). Ecohydrological modeling can also simulate the soil phosphorus cycle continuously over long periods, which can assist in understanding the temporal variation of terrestrial phosphorus (Lou et al., 2015). At the same time, remote sensing provides geographic data at varying resolutions, which can be used to describe changes in the land surface at different scales (Shi et al., 2016). By applying these methods together, more accurate descriptions of the terrestrial phosphorus cycle can be obtained in comparison to previous methods.

The purposes of this study included: (1) building a new approach to calculating terrestrial legacy-P using ecohydrological modeling and remote sensing; (2) mapping the spatial distribution of terrestrial legacy-P; (3) simulating long-term variations in terrestrial legacy-P; and (4) obtaining an accurate estimate of terrestrial legacy-P.

2. Methods

2.1. Summary of terrestrial legacy-P calculations

In this study, ecohydrological modeling and remote sensing were combined to calculate terrestrial legacy-P (Fig. 1). The Ecohydrological Assessment Tool-Phosphorus model (EcoHAT-P) was selected to describe the detailed phosphorus cycle in soil and plants (Liu et al., 2009; Yang et al., 2011; Lou et al., 2015). Multiple sources of remote sensing data were used to drive the model as well as to discretize the land surface information and model results. The specific steps were as follows:

Step 1 Remote sensing, meteorological, *in situ*, and statistical data were used as inputs driving the EcoHAT-P model. The model's output was used to calculate the background values of phosphorus in the soil and consumed annually by crops as well as the soil phosphorus loss due to surface runoff, interflow, and soil erosion. All results were produced in image grid format, making them spatially discrete.

Step 2 Annual total soil phosphorus simulation: The total outflow (natural loss and crop consumption) was subtracted from the total inflow (background levels and fertilizer application).

Step 3 Annual legacy-P calculation. The annual concentration of legacy-P in the soil was calculated using the threshold method. Environmental chemistry studies indicate that inorganic Al-P and Fe-P are the majority components of legacy-P in soil (Liu et al., 2014); in the intensively developed agricultural area of China's Sanjiang Plain, Al-P and Fe-P accounted for 15.4% and 19.0%, respectively (Qin et al., 2006). This study chose 34.4% as the threshold (the sum of Al-P and Fe-P in the study area's soil). A cropland mask was then used to filter for the two main agricultural land-use types in this area (dry land and paddy land), allowing the legacy-P soil concentrations and spatial distribution to be obtained. Soil phosphorus at the end of the first year was used as the background value in the next year. In this way, legacy-P was calculated for each year.

Step 4 Spatial calculation and analysis. GIS tools were used to find accurate quantity and spatial distribution characteristics of terrestrial legacy-P. Spatial calculations included a summation of pixel values and a multiplication of the masked map and legacy-P images. Spatial analysis included image classification and clustering, through which the spatial heterogeneity and distribution features were displayed for the study area. The results were then used to address the three questions put forward in the introduction.

2.2. Ecohydrological model description

The EcoHAT-P model is driven by remote sensing data and is based on chemical and physical processes (Liu et al., 2009; Lou et al., 2015). EcoHAT-P simulates the phosphorus cycle in the soil using three integrated sub-models: fertilization, mineralization, and decomposition and inorganic adsorption. The model also simulates the plant phosphorus cycle using four integrated sub-models: vegetative net primary production (NPP), vegetatitive production distribution, plant nutrient absorption, and vegetatitive litter production (Table 1). All sub-models were inserted into EcoHAT-P and programmed by Interactive Data Language (IDL). The EcoHAT-P model thus allowed soil total phosphorus concentration (i.e. soil background values) to be calculated in each grid cell from 2000 to 2015.

2.3. Site description

The Sanjiang Plain (43°49′55″ to 48°27′40″N, 129°11′20″ to 135°05′26″E) (Fig. 2) was selected as the study area due to its