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Phosphorus risk in an intensive agricultural area in a mid-high latitude region of China

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ABSTRACT

The content and status of phosphorus (P) in agricultural soil have become critical environmental concerns because of the risk of excessive P reaching adjacent water bodies through leaching or runoff. The Sanjiang Plain, an important commercial grain base, is the largest swampy low plain in a mid-high-latitude region in China. The increasing risk of P leaching threatens the area's ecology and agricultural security, particularly because there have been more than 60 years of build-up of P in the soil as a result of intensive agricultural development. A remote sensing-driven model was used in this study to simulate the total phosphorus in the Sanjiang Plain soil from 2000 to 2010. A grid-random sampling method was employed to test the validity of the model in a typical in situ experimental area. Meanwhile, spatial analysis methods were used to analyze model outputs. The results show a significantly increasing trend in the area with higher concentrations of P in the Sanjiang Plain, phosphorus accumulation in the soil and an increasing area at risk of phosphorus leaching; among all land use types, cultivated land and water bodies were observed to have a higher phosphorus risk. We conclude that the growth in farmland converted from forest or wetland and the use of excessive fertilization to maintain high crop productivity are the two principal factors resulting in the growing concentration of soil P. The risk of higher phosphorus in the study area will pose a serious threat to the quality of both surface and ground water, which has important ramifications for future agricultural management and non-point source control in this agricultural area of the mid-high latitude region.

1. Introduction

Phosphorus geochemistry is of agronomic and environmental importance. P, as one of the primary nutritional elements, is essential for terrestrial and aquatic plants and animals (Yang et al., 2012). Due to its low availability, P is also the most limiting factor for crop yield (Cheng et al., 2011; Qiao et al., 2013). In many regions worldwide, to match increasing food demand from population increases, mined rock P or anthropogenic P additions to farmlands have been necessary to maintain grain yields (Duan et al., 2011; Townsend and Porder, 2012). Long-term P fertilization causes significant accumulation of soil P, which represents a growing threat to the aquatic environment (Bolland et al., 1996; Zhuang et al., 2007). Runoff is the primary way that P migrates from soil to water bodies, but vertical P leaching draws more attention because it is another important vehicle for P loss from soil with high P or high organic matter (Djodjic et al., 2004; Sharpley et al., 1994). The build-up of P, and the potential for P leaching, represent a critical risk to water quality and eco-environmental safety.

The mid-high latitude region in China is the core crop-production area in Northeast Asia. A very smooth slope grade, advantageous water condition and a natural supply of soil organic matter provide the region with great potential for reclamation (Richardson and Ho, 2003). In response to an increased demand for cropland, this region experienced more than 60 years of intensive agricultural activity; widespread land reclamation occurred during this period and its large area of natural wetland was diminished (Ouyang et al., 2013; Song et al., 2008). Sanjiang Plain is the largest swampy low plain in China, and it also represents the most important base for grain commodities in the country (Shi et al., 2007; Xu et al., 2012). According to local land use policy, virgin land, such as wetland and forest, have been reclaimed as paddy land and dry land, and increasing fertilization has been used to attain higher, stable crop production (Cao et al., 2006; Song et al., 2008).

Research on the concentration of soil P has been primarily in situ experiments or studies conducted on a small spatial scale, and soil chemistry

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tests have been the predominant method for obtaining P concentration data. In larger areas, the combination of chemistry tests and a simple empirical model are the preferred way to obtain the P data (Guo and Ma, 2011; Liu and Song, 2010; Wang et al., 2010; Wang et al., 2012a, 2012b). These classical methods can help us better understand the concentration of soil P at a small scale, and precise results can be obtained from sampling points. However, at a large spatial scale (e.g., basin scale) and for long time series the chemistry method is not effective; although some statistical models are used, these simple models cannot express the cyclical and dynamic mechanism of soil P in nature.

Many complex mechanism models that can simulate and describe the migration and conversion of nutrients or heavy metals have been developed in recent decades, including the SWAT model, the PSYCHIC model, the EPIC model, the AnnAGNPS model, the ANSWERS model and the CREAMS model (Beasley et al., 1980; Knisel, 1980; Neitsch et al., 2005; Paul et al., 2008; Storm et al., 1988; Williams, 1990; Yuan et al., 2005). Among these models, the SWAT model has been used and validated in many countries and regions (Gassman et al., 2007). The statistical model coupled with a P-cycle mechanism model, or with a P-cycle model coupled with hydrological and erosion models, are widely used to simulate P migration and conversion (Hao et al., 2006; Zheng et al., 2009). Models such as the CREAMS model and the EPIC model can only simulate nutrient content at the catchment scale, but large-scale simulation of P-content and P-cycle using these models is not possible. One of the most efficient techniques for resolving the large-scale problem is the use of remote-sensing techniques. The simulation of P-concentration at large temporal and spatial scales necessitates a remote sensing driven model that can effectively describe the physical mechanism of the P cycle.

The Ecohydrological Assessment Tool (EcoHAT) (Dong et al., 2013; Liu et al., 2009; Wang et al., 2009, 2010; Wang et al., 2011; Yang et al., 2011) is an ecohydrological simulation system that can comprehensively simulate regional ecohydrological processes based on the physical and chemical mechanisms. EcoHaT integrates hydrological cycle processes, nutrient cycle processes and the plant growth process, as well as taking into account the nutrient cycle and vegetation growth in the hydrological cycle. EcoHAT couples with remote sensing models to invert land surface parameters, providing a spatial data source for ecohydrological process simulation. Driven by remote sensing, EcoHAT takes full advantage of remote sensing in resolving the problem of simulating P-concentration in soil on a large scale and with a time series. At the same time, the EcoHAT system embeds GIS spatial analysis tools, which can analyze the simulation results effectively (Liu et al., 2009).

The objectives of this study are as follows: 1) to study the variation in the area and the position of P risk in the soil, thereby obtaining the spatial and temporal variation pattern in the Sanjiang Plain; and 2) to obtain the concentration of P in the soil from 2000 to 2010 (11a) in the Sanjiang Plain, which has experienced more than 60 years of intensive agricultural development, using a remote sensing driven P model in EcoHAT as an alternative to soil chemistry methods. The study area, the input data for the model, and the framework of the P model in the EcoHAT system are introduced in detail in Section 2. In Section 3, the simulation results are analyzed, and the geographical variation in the concentration of P at different levels, as well as the potential for P leaching, is also described. In Section 4, the reliability and uncertainty of results, the factors driving P accumulation and the future risks associated with phosphorus in the Sanjiang Plain are discussed.

2. Methodology

2.1. Study area

The Sanjiang Plain (43°49′55″–48°27′40″N, 129°11′20″–135°05′26″ E) (Fig. 1) is an area of low relief within the Heilongjiang Province of China, with a total area of 108,900 km^2, occupying 22.6% of the total area of the Heilongjiang Province. Three rivers, the Amur River, the Songhua River, and the Ussuri River, constitute its major waterway system and are responsible for the alluvial deposits in this area (Song et al., 2008; Yang et al., 2012). The climate is temperate and humid and mid-humid continental, with an annual average temperature of 1.9 °C. January is the coldest month, with an average temperature of −20 °C, July is the hottest month, with an average temperature of 22 °C, and annual precipitation ranges from 500 to 600 mm. This region experiences seasonal freeze, and from November to April the soil undergoes frequent freeze–thaw cycles. The main soil types in the area are meadow swamp soil, humus swamp soil and peat swamp soil. Natural soil fertility is very good in the Sanjiang Plain; maize, wheat, soybean and other plants have the advantage of excellent growing-conditions. The plain is thus one of largest commodity crop bases in China. Crop production there plays a critical role in China's crop safety, even influencing Northeast Asia's crop safety. The large area of wetland in the Sanjiang Plain is another of its notable features. The total area of wetland was 1,100,000 ha in 2003 (Richardson and Ho, 2003), making it the most notable wetland in all of China.

The Bawujiu Farm (Fig. 1), located in the northeast portion of the Sanjiang Plain in Heilongjiang Province, provided the case study site for this research project. The climate condition in the Bawujiu Farm is similar to the Sanjiang Plain. Its soil types include alluvium, loamy meadow grassland, clayey meadow grassland, lessive meadow grassland, gley meadow grassland, swamp soil, peat swamp soil, dark brow forest soil, albic soil, meadow lessive and clay lessive. These soil types are very common and typical in the Sanjiang Plain. Maize, rice and soybean are the primary crops in the Bawujiu Farm, similar to the Sanjiang Plain as a whole. The Bawujiu Farm is itself a record of the mass agricultural development in China. The current farm site was covered in extensive wetland and forest before its establishment in 1956; since then it has been affected by widespread land reclamation (Xu et al., 2012). In addition, the high level of crop production, the yearly increase in fertilization usage, the excess reclamation, and the local land use policy that seeks to convert more wetland and forest to farmland led us to choose this farm as our typical experimental site.

2.2. Data and experiment

2.2.1. Data

The input data (Table 1) for the model include multisource remote sensing data and production, meteorological data, in situ experiment data, and survey and historical data. Multisource remote sensing data and meteorological data come from public free data platforms (e.g., USGS: United States Geological Survey, http://www.usgs.gov/pubprod/); other data resources are from in situ experiments and statistical data. All the original input data were processed by IDL (Interactive Data Language) programs; IDL has the ability to process batched mass remote sensing images. Some of the data were resolved by the software ENVI5.0 or ArcGIS10.0. All the input data were imaged, then set according to a uniform projection and coordinate system. The spatial resolution of the input data is also a key step because only if the input data have the same spatial resolution can the P simulation model run smoothly, but different input data may have different spatial resolutions. For example, Landsat TM (Thematic Mapper) data have 30 m spatial resolution, while the MODIS (Moderate-Resolution Imaging Spectral Radiometer) data we used have 1000 m spatial resolution. At the same time, we tried to use GLDAS (Global Land Data Assimilation System) data to improve our spatial–temporal (three-hourly) resolution of meteorological data, but the GLDAS data have a coarse spatial resolution of 25 km. To obtain the uniform 1000 m spatial resolution we want to input into the model, we resampled and used some downscaling methods; the validation of the downscaling result was satisfactory.

2.2.2. Experiment for model validation

To validate the performance of the P model in EcoHAT (EcoHAT-P), we sampled at the Bawujiu Farm at the end of April, 2011 (Fig. 1) by