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Modeling of soil available phosphorus surplus in an intensive wheat–maize rotation production area of the North China Plain

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ABSTRACT

The excessive application of phosphorus fertilizer has caused available phosphorus (AP) surplus in cultivated soils. By using the Soil and Water Assessment Tool (SWAT), the soil AP surplus and its relationship with fertilization and environmental changes was estimated for the wheat-maize rotation production area in the Baiyangdian basin, which is a typical arid region in North China Plain. Due to the little runoff, the model was validated by the measured AP concentration in deep soil profiles of the cropland. The results indicated that with an evident overuse of phosphorus fertilizer, the average rate of AP surplus in soils in the basin was about 10.3% of the applied fertilizer. A large part of the applied phosphorus (57.2%) was accumulated in active mineral forms. The phosphorus fertilizer recovery efficiency averaged 41.4%, ranging between 29.3% and 51.7%. This lower efficiency was expected to be the main reason for the serious AP surplus in cultivated soils. As a result, it was predicted that for every 100 kg ha^{-1} of P fertilizer added, the AP of the plough layer (0–20 cm) will be increased by an average of 3.35 mg kg^{-1} (around 10 kg P ha^{-1}) in the study area. Furthermore, the soil AP surplus was predicted to reach a higher level under the condition of lower precipitation because of less runoff-induced erosion and leaching to deeper layers. From 1993–2010, the soil AP accumulation was 445.7 kg ha^{-1} in the study area, with an average accumulation rate of 24.8 kg ha^{-1}yr^{-1}, which belongs to the highest level worldwide. Through combining the measured data with the simulated results, it was suggested that excessive phosphorus fertilizer application along with low phosphorus fertilizer recovery efficiency will increase the risk of P leaching, which threatens the security of groundwater.

1. Introduction

Phosphorus (P) is one of the essential nutrients for plant growth, as it plays an important role in energy storage and transfer. In order to guarantee high yield, excess application of P fertilizer is practiced widely throughout the world (Tilman et al., 2002; Good and Beatty, 2011), especially in China and Brazil (MacDonald et al., 2011). Meanwhile, high P fertilizer application is also typically associated with an inefficient P utilization, with a reported range between 10% and 47% (Tang et al., 2008; MacDonald et al., 2011). Consequently, a large amount of residual P accumulates in cultivated soils, changing into less soluble and more stable forms (Selles et al., 1995). The soluble P (available P, AP) in soils not only can be transported into the rivers and lakes through runoff-induced erosion, but also can move downward in the soil layers, finally reaching the groundwater table. These processes cause environment pollution such as eutrophication, and threaten the security of surface water and groundwater in many countries of the world (Smith et al., 1999; Conley et al., 2009; Le et al., 2014; Wang et al., 2014a; Özcan et al., 2017; Wang et al., 2018).

To meet the growing food demand, China uses more P fertilizer than any other country (Huang et al., 2017). The average level of P fertilizer applied was approximately 123.2 kg P ha^{-1} (amounts to pure P, the same below), higher than the world average (about 45.0 kg P ha^{-1}). The excessive fertilization is largely due to the imperfect legislation. However, in 2015, China introduced a zero-growth action plan for fertilizer use by 2020, which regulated strict control of the amount of P fertilizer, especially in the northern region. Winter wheat and summer maize rotation is the dominant crop system in the North China Plain (NCP), in which the yield of wheat accounts for more than 60% of the country's total production, as calculated from the data in the Statistical Yearbooks. P fertilizer applied here often exceeds the country average by two times or more (Wang et al., 2015; Xin et al., 2016). Owing to the

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depleted surface runoff and submerged groundwater levels in the NCP in the recent decades (Sun et al., 2006; Leng et al., 2015), excessive P fertilizer in cultivated soils is likely to accumulate in unsaturated zones and leach downward, rather than draining into the surface water system (Li et al., 2011). The risk of AP leaching is invisible but irreparable; so, it is important to predict the surplus AP and accumulation trends in soil. It is helpful for government and farmers to determine the quantity of P fertilizer to be applied to ensure the most efficient crop growth without surpassing the environmental thresholds.

Soil AP surplus and accumulation and its response to agricultural management was determined mostly through field investigations such as soil sampling (Liu et al., 2005; Bouraoui and Grizzetti, 2014), soil column experiments (Ribbe et al., 2008; Zhang et al., 2016), and plot trials (Bonaiti and Borin, 2010; Xin et al., 2017; Tolomio and Borin, 2018). Based on numerous field investigations, an acute increase in soil AP concentration during past decades and a significantly positive relationship between soil AP and P fertilizer application was found in many regions of the world (Panagopoulos et al., 2007; Constantin et al., 2010; Muschietti-Piana et al., 2018). However, field experiments are valuable for finding out the theoretical effects of controlled farm management on variations in soil AP, which is usually difficult to generalize in terms of actual agriculture production. In addition, several statistical models with input and output variables have been developed for estimating soil AP accumulation (Schoumans and Groenendijk, 2000; Grizzetti et al., 2003; Mekonnen et al., 2017; Tootoonchi et al., 2018). Although such models were validated in some regions (El-Khoury et al., 2015; Wang et al., 2015; Shrestha et al., 2016), they were usually tested only within a certain area, and the accuracy tends to be more biased after being extended to a larger scale (Ng et al., 2010).

Therefore, a regional process-based model is thought to be an effective tool to estimate soil AP accumulation and its relationship with fertilization and crop yield in a large landscape. The SWAT model contains a completed calculation of the P cycle in the environment, and it has been widely used to predict the fate of AP generated from agricultural activities (Panagopoulos et al., 2007; Xin et al., 2008; Yin et al., 2011; Lu et al., 2016; Shrestha et al., 2016). However, comparing to surface erosion, the model has been rarely applied to simulate soil AP accumulation in an area with little runoff. Baiyangdian (BYD) basin, which is located in the NCP, is a good area for assessing soil AP accumulation, because there is intensive cropland rotation but almost no surface runoff here. As such, we designed this study to: (1) calculate the magnitude of soil AP surplus; (2) determine the effects of fertilization, crop yield, and environmental changes (particular, variation in precipitation) on soil AP surplus; and (3) estimate soil AP accumulation rate and distribution in the wheat–maize rotation production area of the BYD basin.

2. Materials and methods

2.1. Study area

Taking the BYD lake as outlet, the BYD Basin (113°39′–116°20′ E, 38°23′–40°09′ N) is located in the northwest of the NCP, comprising about 19,000 km^2 of the Tai-hang mountainous region and about 13,000 km^2 of the piedmont plain region (Fig. 1). Rotation cropping of winter wheat and summer maize, accounting for 37.6% of the plain area, is the dominant crop system in the plain region, as well as in most areas in the NCP. In the past decade, the average yield per unit area was 6.0 t ha^{-1} and 6.3 t ha^{-1}for winter wheat and summer maize in the basin, respectively. It represents an intermediate level in the NCP (total yield of 6.0–16.7 t ha^{-1}) (Fan et al., 2016). The crop growth in the basin depends mainly on the application of nitrogen and P fertilizers, with an average application amount of 461.1 kg N ha^{-1} and 239.5 kg P ha^{-1}, respectively.

The BYD basin is characterized by a semiarid monsoon climate, with an annual average rainfall of 560.7 mm, of which almost 80% is concentrated from July to September. Since the 1990s, the precipitation and runoff has reduced dramatically (Yang and Mao, 2011). Combined with the interception effect of reservoirs, most rivers originating from the mountainous area and previously flowing into the BYD lake have even been drying up (Yuan et al., 2017).

2.2. Phosphorus movement in the SWAT model

Owing to the limited solubility of P in soils, soil P has three major forms: AP in the soil solution, fixed mineral P in the particulate state (PP), and organic P associated with humus (OP). In the cropland, P can be added to the soil through fertilizer, manure, or crop residue application, and be removed from the soil by plant uptake and erosion. Meanwhile, it can also be converted between different forms.

The SWAT model monitors three mineral P pools (solution, active, and stable) and three organic P pools (active, stable, and fresh) in the soils (Neitsch et al., 2011). AP, which can be taken up by the plants and also be removed through erosion by runoff, is the P in the solution pool. Fertilization (that adds pure P) is correlated with the solution pool directly. Manure and crop residue, respectively, can be added to the active and fresh organic pools from which partial OP can be mineralized and put into the solution pool. Furthermore, the solution pool is in rapid equilibrium with the active mineral pool in the model (several days). This balance is governed by the P availability index (*pai*) which specifies the fraction of P fertilizer that is in solution after the rapid reaction period, shown as follows:

$$\begin{cases} AP_{act} = AP - 0.2PP\left(\frac{pai}{1-pai}\right) \; if \; AP > 0.2PP\left(\frac{pai}{1-pai}\right) \\ AP_{act} = 0.1\left[AP - 0.2PP\left(\frac{pai}{1-pai}\right)\right] \; if \; AP < 0.2PP\left(\frac{pai}{1-pai}\right) \end{cases} \tag{1}$$

where AP_{act} (kg P ha^{-1} d^{-1}) is the rate of P movement between the soluble and the active mineral pools, calculated by day step; AP (kg P ha^{-1}) is the amount of P in the solution pool; the factor $0.2PP$ (kg P ha^{-1}) is the amount of P in the active mineral pool (the rest of 0.8 P P is thought to be in the stable mineral pool); and the constant of 0.1 represents the rate of flow from the active pool to solution is 1/10th the rate of flow from solution to the active pool (RãJan and Fox, 1972)

So far, the soil AP surplus in the cropland can be calculated using the following equation:

$$AP_{surp} = AP_{ini} + AP_f + \beta_m OP_m + \beta_r OP_r - AP_{up} - AP_{runoff} - AP_{act} \tag{2}$$

where AP_{surp} (kg P ha^{-1}) is the surplus AP in the soil; AP_{ini} is the initial AP concentration in the soils (mg kg^{-1}), converted to a mass basis by using Eq. (3) below; AP_f (kg P ha^{-1}) and OP_m (kg P ha^{-1}) are the amounts of P fertilizer (amounts to pure P) and applied manure P, respectively; OP_r (kg P ha^{-1}) is the amount of P in straw residue; β_m and β_r are the rate coefficients for mineralization of the humus active organic nutrients and residue fresh organic nutrients, respectively; AP_{up} (kg P ha^{-1}) is the total P uptake by crops (grain and straw); and AP_{runoff} (kg P ha^{-1}) is the amount of P removed by runoff.

$$\frac{conc \bullet \rho_b \bullet depth}{100} = \frac{kg}{ha} \tag{3}$$

To convert concentrations to kg ha^{-1}, we used Eq. (3), in which *conc* (mg kg^{-1}) is the concentration of P in a layer; ρ_b (g cm^{-3}) is the bulk density of the layer; and *depth* (mm) is the depth of the layer.

2.3. Model setup and validation

The SWAT2012 was setup for the BYD basin including the northwestern mountainous area and the southeastern plain area. Topographic data used for watershed delineation was based on the 90-m-grid DEM of the Shuttle Radar Topography Mission (Fig. 1). Combination of a land use map derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) data, a 250-m-grid soil map, and