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Phosphorus flow management of cropping system in Huainan, China, 1990–2012

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ABSTRACT

The rapid increase in phosphorus (P) use in cropping has raised concerns regarding the conservation and environmental impact of P. This study applied a partial substance flow analysis (SFA) to establish a dynamic model to evaluate the changes in the P flows from 1990 to 2012 in the cropping system of Huainan City, a typical agricultural region in central China. Based on this model, the P flows, P losses, P accumulations, and phosphorus use efficiencies (PUEs) during this period were identified and quantified using data from official statistical databases, questionnaires, face-to-face interviews and published literature. The results indicate that the total P input, P output, and P stock increased during these years. The increased P input was mainly caused by the dramatic increasing application of chemical fertilizer and the large-scale livestock excrement, while the great amount of harvested grains increased the P output. With the high application of the P input, the P stock including stored straw and soil accumulation also grew during these years. The P losses and P accumulations generally increased, except for 1995–2005, as a result from the substantial decrease in the cropland. Consequently, the PUEs in these years were not promising and were as low as approximately 30%, with great straw accumulation and loss. Based on the observed P flow of the cropping system in Huainan, this study provides some recommendations for improving P management. The quantifiable science-based methods that were used in this study may be applied to improve the resource management efficiency of the cities/counties and the water quality of the surrounding area.

1. Introduction

Phosphorus (P) is an essential element for crop growth in the form of fertilizers containing P (Cordell et al., 2009). However, P-containing fertilizer has been applied inefficiently in crop production (Iho and Laukkanen, 2012). When P fertilization exceeds the removal of P by the crop, most of the surplus P will remain in the soil to add to the P reserve (Hooda et al., 2001). Excessive soil P levels have been linked to high P losses in runoff and may increase the potential eutrophication of surface waters (Elliott et al., 2002; McDowell and Trudgill, 2000; Sims et al., 2000). Meanwhile, modern agriculture relies heavily on chemical fertilizers, which contain P that is derived from phosphate rock, while the reserves of phosphate rock for mining are limited. It has been claimed that phosphate rock reserves could be completely depleted within 50–100 years at the present rate of consumption (Cordell, 2010; Steen, 1998; Smil, 2000), and the peak P could occur around 2033 (Cordell et al., 2009). It has been suggested that the conservation and recycling of P could help sustain crop production and reduce the pollution of surface waters (Carpenter, 2008). Considering the contribution of the cropping activities to the P consumption and loss, there is a need to improve P resource management.

To improve P management, an indispensable first step is to trace and quantify the P flows in these cropping processes. An approach has been adopted to reflect the field vulnerability of P loss, one type of P flow (Hughes et al., 2005; Lemunyon and Gilbert, 1993), while the weight and P loss rating of each source seems to more qualitatively lead to the only P loss ranks of the crops. Thus, it is important to analyze the P flows with a quantitative method. Though there are some quantitative methods developed, which mainly based on monitoring (Bechmann et al., 2005; McDowell and Trudgill, 2000; McDowell et al., 2001), Geographic Information

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System (GIS) (Eastman et al., 2010), or soil erosion and P loss formulas (Leone et al., 2008). These methods only calculate the P loads not the P flows, which cannot trace the sources of these flows and interpret complex environment–anthropogenic interactions. Nevertheless, the balance between the input and output which is a tool for analyzing the P flows serves as a performance indicator for P management. Attaining a proper nutrient balance while producing optimum crop yields can only be done by adopting the best management practices for the soils, crops, and nutrients (Bast et al., 2009; Wijnhoud et al., 2003).

Because of these considerations, the mass-balance method might be appropriate for evaluating the P flows and P loss to the water environment. Based on the mass balance principle, which is also a decision tool for P management, Brunner (2010) has suggested the substance flow analysis (SFA), which systematically assesses the flows and stocks of one substance within a system that is defined in space and time and connects the sources, pathways, intermediates and final sinks of the substance (Brunner and Rechberger, 2003). This methodology is widely used to quantify the flows of carbon (Grayston et al., 1997), nitrogen (Baker et al., 2001; Olsthoorn and Fong, 1998), and oxygen (Hansen and Lassen, 2003), etc. In contrast to these studies, we focus on the flows of P in a cropping system that is associated with planting. It is defined as the management of a cropping pattern to optimize benefits from a given resource base under specific environmental conditions (Zandstra, 1977).

Though there are studies analyzing the P balance of cropping systems in some cities (Li et al., 2010; Wu et al., 2012; Yuan et al., 2011a, 2011b, 2011c) or on several main crops (Ma et al., 2011), these studies calculate the flows statically and could not conclude the changes in the P flows. As it is meaningful to analyze the P flows on a time scale which can trace the change of the P flows and their drivers. Some studies mainly evaluate the P flows of cropping systems over time at the global (Bouwman et al., 2009; Cordell et al., 2009; Liu et al., 2008), national (Antikainen et al., 2005; Chen et al., 2008; Cooper and Carliell-Marque, 2013; Senthilkumar et al., 2012; Suh and Yee, 2011), watershed (Bast et al., 2009; Bennett et al., 1999; Drolc and Koncan, 2002; Iital et al., 2003; Kobayashi and Kubota, 2004), provincial (Wu et al., 2014), and city levels (Neset et al., 2008; Qiao et al., 2011). Few previous studies have examined the changes over time in P flows at the city level, especially in China. In particular, P management measures have been inadequately proposed.

This study evaluates changes over time in the P flows, P losses, P accumulations, and P-use efficiencies (PUEs) in response to changes in the P inputs and P outputs with a dynamic mass-balance model across a city. Furthermore, the case study area of Huainan City in the Anhui Province of China was selected, and the P flows, P losses, P accumulations, and PUEs in the cropping system of this city from 1990 to 2012 were identified and quantified. Huainan City, a farming region, exhibits distinctive agricultural features that are typical of central China. Moreover, because Huainan is a main farming region, a large amount of P fertilizer is consumed. Therefore, the P management of the cropping system in this city was proposed. This study addresses the following aspects:

(1) Quantify the P flows in the cropping system of Huainan City from 1990 to 2012.
(2) Determine the P losses/accumulations/-use efficiencies of the cropping system in Huainan City from 1990 to 2012.
(3) Analyze the P-reuse/recycle in the cropping system of Huainan over the 23 years.
(4) Provide specific P management based on the results of a P flow analysis.

2. Methods

SFA rests on the mass balance principle and the first law of thermodynamics. All of the essential flows of a given substance into, out of, and through a geographically bounded system are included, and the flows between the environment and human economy are defined (Van der Voet, 2002). In this study, a partial SFA on the flows of P in the cropping system of Huainan City was conducted. Partial SFA is a kind of SFA, which is also derived from the law of mass conservation and allows scientists to estimate how P flows through the cropping system. Such as in Chen et al.'s (2008) study, this method was also made herein to understand the key stocks and flows of P in agriculture.

2.1. Study area

Huainan City is located in the center of Anhui Province, near the capital city of Hefei. This city includes six counties with a total population of 2.44 million, containing 1.12 million urban populations and 1.32 million rural populations at the end of 2012. This city covers 113,313 cultivated ha (SBAP, 2013) and is one of the most developed cities in Anhui, representing a typical agricultural region of central China. Meanwhile, Huainan has the abound phosphate rock. The main crops, i.e., wheat, rice, and maize, occupy an important position in Huainan. Moreover, crop production consumes large amounts of P fertilizers, including 48,341 t of compound fertilizers and 26,524 t of phosphate fertilizers in 2012 (SBAP, 2013). Through interviews with the local environmental protection bureau, it was found the environmental impacts that are caused by increased P levels have become increasingly significant in Huainan City, exceeding the self-cleaning capability of the surrounding water, due to the drainage of P from planting, livestock breeding and rural habitation. While the city has already introduced management measures to address these problems, the large amount of P that is drained from planting and livestock breeding remains untreated, seriously impacting human living conditions and production. This study analyzed in China is meaningful, and may provide a good basis for the related studies in other regions.

2.2. System definition

In this study, the geographical boundary of the analyzed system was the land boundary of Huainan City, which contains both the urban area and rural area. The system referred to P flows that are associated with the planting of crops, mainly rice, wheat, rapeseed, peanut, sesame, cotton, vegetables and fruits, maize, beans, and potatoes basing on their much larger amounts than other crops. Atmospheric deposition, irrigation, seeds, chemical fertilizers, pesticides from the fertilizer industry, rural residents' and livestock excrement that was applied to the field were considered P inputs to the system. Considering the differences between the consumed feed and the field application rate, this study divided the livestock excrement that was applied to the field into large-scale breeding excrement and domestic breeding excrement. It is noted the livestocks contained mainly pig, cattle, sheep, and poultry considering their larger amounts than other livestocks. Grains, straw feed used for livestock breeding, erosion and runoff were considered P outputs from the system. The P losses from cropland occur mainly via erosion and runoff (Liu et al., 2008). Soil accumulation and straw stored in the field were considered the P stock/surplus of the system. The framework of phosphorus flows in cropping system was illustrated in Fig. 1. The analyzed time period ran from 1990 to 2012. It is noticed there's no obvious change from the basic data gained mainly from the statistical database in every five years. Meanwhile,