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Life-cycle phosphorus use efficiency of the farming system in Anhui Province, Central China

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ABSTRACT

The rapid increase of phosphorus (P) use in farming has raised concerns regarding its conservation and environmental impact. Increasing the P use efficiency (PUE) is an approach to mitigating these adverse impacts. In this study, we applied substance flow analysis (SFA) to establish a life-cycle P use efficiency model to determine the life-cycle PUE of the farming system used in Anhui Province in 2011, which is typical of the agriculture practiced in central China. Based on this model, the P flows and PUEs of five subsystems were identified and quantified: crop farming, crop processing, livestock breeding, rural living, and urban living. The three largest P flows were found in the crop farming and livestock breeding subsystems; it can therefore be concluded that these subsystems have substantial impacts on the entire farming system. In contrast, the PUEs of crop farming, rural consumption, and livestock breeding subsystems presented the three lowest PUEs (58.79%, 71.75%, and 76.65%, respectively). These results were also consistent with the finding that the greatest P losses occurred in crop farming and livestock breeding. Consequently, the study proposes that great potential exists for increasing PUEs in the farming system of Anhui, and several of the most promising measures could be combined for improving PUEs. Finally, the study assesses data quality and presents a sensitivity analysis for use in interpreting the results. The study also shows that improving PUE and decreasing P losses in farming systems through improved nutrient management must be considered an important issue, and this study represents valuable experience in resource conservation and agricultural development in China.

1. Introduction

Phosphorus (P) is one of the essential nutrients for plant growth, and its input is necessary to maintain profitable crop productivity (Lin et al., 2009). In agriculture, this nutrient has been applied in increasing quantities in chemical fertilizers since the early 20th century (Neset et al., 2008). The P for chemical fertilizer is produced by ore mining. While the reserves of phosphate rock worth mining are limited, most frequently a time horizon of 50–100 years has been suggested (Cordell et al., 2009). In addition, P may accumulate in soils from the excessive application of fertilizers or manure relative to crop needs (Meals et al., 2008). Excessive soil P levels have been linked to high P losses in runoff, increasing the potential for surface water eutrophication (Elliott et al., 2002; McDowell and Trudgill, 2000; Sims et al., 2000). Consequently, there is a need to conserve P resources to prevent a future collapse of agriculture (Vaccari, 2009).

The cycle of utilizing and transforming P resources in farming is as follows: P is added to cropland in mineral (chemical) fertilizers and organic waste (livestock and residents' manure) prepared by fertilizer manufacturers; then, P flows to animal production in feed and to household consumption as food (Ma et al., 2010; Neset et al., 2008). The discharge of P to natural waters may also result in eutrophication. To improve P resource management, there is a need to trace and quantify P flows and P use efficiencies (PUEs) in these processes.

Early studies of P flows mainly utilized models representing the input–output balance of P or the P mass balance (Ekholm et al., 2005; Iital et al., 2003; Kobayashi and Kubota, 2004; Meals et al., 2008). These studies often regarded farming systems as a "black box" and calculated the system inputs (inflows), outputs (outflows), and accumulations based on the mass balance principle, tracking and analyzing P utilization and transformation ineffectively, leading to poor P management systems. Substance flow analysis (SFA) is considered a fundamental tool for improving P management (Brunner, 2010) and is applied to analyze the flows and stocks of a single substance or a coherent group of substances based on the principle of mass balance (van der Voet, 2002). This type of

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analysis covers all actions in a studied system, including the extraction or harvesting of material resources, chemical transformation, manufacturing, consumption, recycling, and the final disposal of materials (Antikainen, 2007). The methodology is widely used to quantify the pathways of metals such as mercury (Stephen, 1995), zinc (Spatari et al., 2003), copper (Graedel et al., 2004), silver (Johnson et al., 2005), and steel (Jeong et al., 2009) as well as nonmetals such as carbon (Grayston et al., 1997), nitrogen (Baker et al., 2001; Olsthoorn and Fong, 1998), and oxygen (Hansen and Lassen, 2003). In contrast to these studies, we focus on the flows of P in a farming system associated with planting, processing, and consumption in a region within a province.

Meaningful SFA results concerning P flows (Filippelli, 2008; Matsubae-Yokoyama et al., 2009; Saikku et al., 2007; Wu et al., 2012; Yuan et al., 2011) have been published, especially regarding farming systems. These studies have mainly been conducted at global (Bouwman et al., 2009; Liu et al., 2008), national (Antikainen et al., 2005; Chen et al., 2008; Cooper and Carliell-Marquet, 2013; Senthilkumar et al., 2011; Smit et al., 2010; Ott and Rechberger, 2012), watershed (Asmala et al., 2011; Bast et al., 2009; Chen et al., 2009; Wu et al., 2010), and city (Li et al., 2011; Neset et al., 2008) levels; few have been conducted at the provincial/regional level. These studies have also focused mainly on quantifying P discharge from the studied systems and identifying the key sources and paths of pollution (McDowell et al., 2011; Meals et al., 2008; Qi et al., 2007) while often ignoring the PUE in the system. Nevertheless, several studies have examined the PUE in farming systems, mainly at the global (Bouwman et al., 2009) and national (Ma et al., 2011; Suh and Yee, 2011) levels; once again, studies at the regional level are lacking. In addition, these studies focused on proposing measures to increase PUEs from an engineering standpoint, often failing to analyze human activities that lead to P discharge to the environment (Bouwman et al., 2009; Liu et al., 2008; Oenema, 2004; Smil, 2000). Consequently, we selected Anhui Province as a case study. Anhui Province, a farming region, exhibits distinctive agricultural features that are typical of central China. Moreover, because Anhui is a main farming region, large amounts of P fertilizer are consumed. However, the phosphate source rock used to produce chemical fertilizers in Anhui is limited. Thus the first step toward conserving P resources and protecting the environment is to track P flows and increase PUE in the farming system.

The objectives of present study are to quantify P flows and PUEs by applying SFA to the crop farming systems used in Anhui Province and to propose relevant strategies aiming at improving PUEs. In particular, the aims are (1) to develop a life-cycle P use efficiency model of the farming system employed in a region/province based on SFA, (2) to quantify P flows and PUEs in the farming system used in Anhui Province, (3) to determine possible reasons for the low PUEs, and (4) to develop strategies that increase PUE.

2. Methods

2.1. Study area

Anhui Province is located in central China acrossing the basins of the Yangtze River and the Huai River (Shi et al., 2008). Chaohu, which is one of the five largest freshwater lakes in China, is located in the center of the province. The southeastern part of the province, near the Yangtze River, also has many lakes. The capital of the province is Hefei. Anhui includes 16 cities with a total population of 68.76 million; the rural population was 77.07% of the total at the end of 2011. The area represents a typical agricultural region of central China. Anhui covers an area of 139,427 km^2, of which 4184 km^2 is cultivated, comprising 1896 km^2 of paddy land and 2288 km^2 of dry land. Agricultural production is highly intensive. The main crops in Anhui, i.e., wheat, rice, and maize, occupy an important position in China. Moreover, as one of the main farming regions in China, Anhui consumes large amounts of P fertilizers, including 1.34×10^6 t of compound fertilizers and 3.65×10^5 t of phosphate fertilizers per year over the most recent five years (SBAP, 2008, 2009, 2010, 2011, 2012). To conserve the supplies of rock phosphate, the local government distributes the mining rights only to designated companies; this practice leads to a scarcity of raw materials in many companies that produce chemical fertilizers.

2.2. System boundary

In this study, a partial and static SFA is applied to understand the key P flows and PUEs in farming systems in Anhui. It is assumed that all P flows occurred during the same year and that no time lag existed. Data and information regarding the study area were collected for the 2011 period, the most recent year for which P flow inventories were available. The data mainly include statistical data on the amounts of P-containing substances; the proportions of P-containing substances; the amounts of P-containing substances that were harvested, produced, and discharged; and P-containing rates of the substances, and related data. The information mainly relates to farmers' skills in growing crops, weather conditions, residents' incomes, awareness of environmental protection, grain production, and the treatment of wastes from rural residents and their livestock.

The model applied here assumes that the system operates in a steady state. The social metabolism of P, which is caused by natural factors including wind erosion and sediment release, is not considered due to the low levels of P involved and difficult quantification involved. However, imports and exports of P-containing materials are considered. The system boundary of this analysis is illustrated in Fig. 1 and comprises three life stages: planting, processing, and consumption. The first phase is crop farming, the second phase relates to crop processing, and the third phase includes livestock breeding, rural living, and urban living. Thus, the farming system employed in Anhui is primarily divided into five subsystems. The main flows and stocks of P are described in Appendix A. The fertilizer industry produces chemical fertilizers and pesticides, the processing industry produces feed, and waste management disposes of wastes; these items are not included in the farming system and are shown using small dotted lines in Fig. 1. In the relevant literature and concerning the features of the farming system, these three industrial sectors are placed either at the beginning or at the end of the agricultural P cycle, unlike the other five subsystems, which lie at the core of the system and interlink with each other. Data regarding these three sectors are obtained with difficulty.

The crop farming subsystem refers to P flows associated with the planting of crops, mainly rice, wheat, rapeseed, peanut, sesame, cotton, vegetables and fruits, maize, beans, and potatoes. The P inputs into the subsystem comprise air deposition, irrigation, seeds, chemical fertilizers, and pesticides from the fertilizer industry rural residents' and livestock excrement applied to field. Among these sources, chemical fertilizers and the excrement of rural residents and livestock compose the applied fertilizers. The P outputs considered in this subsystem comprise grains, straw feed used for livestock breeding, erosion, and runoff. Part of the straw is returned to the field, which is regarded as P that is recycled within the subsystem. P stocks include soil deposition and straw stored in the field.

The P input of the crop processing subsystem is related to the harvested grains. P outputs include grain used as food (flour, edible rice, maize, and oil products) for rural and urban residents, fodder consumed by livestock, other forms, exports, and production losses. The P surplus, which is part of harvested grains and need to be produced, is considered as the P stock within the subsystem.