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A multi-level analysis of China's phosphorus flows to identify options for improved management in agriculture

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ABSTRACT

Phosphorus (P) is a finite natural resource and is essential for food production. The amount of P involved in food production in China relative to the increase of food production has increased dramatically over the past decades, which has led to serious environmental pollution. Because of China's enormous share in global P fertilizer production (30%) and consumption (37.5%), it evidently plays a crucial role in developing a more sustainable use of this essential resource for agriculture. We performed an integrated analysis of the P flows, P stocks, P utilization efficiencies (PUE) and environmental implications at the national level in China for the year 2010, complemented with an analysis at regional, county and farm levels. The static Material Flow Analysis approach based on the law of mass balance was used. We found that P accumulation in the arable land and P losses in the livestock raising industry are the major contributors to environmental pollution. Improving the PUE in arable land and the livestock raising industry, on the basis of the actual demands combined with efforts to promote the use of residual soil P on arable land and the recycling of organic manure and wastes, will significantly reduce the consumption and losses of P from the food chain, and will slow down the depletion of this finite natural resource.
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1. Introduction

1.1. The recent history of the phosphorus (P) cycling in agriculture in China

As a country with a five-thousand-year-old agriculture, China is feeding 22% of the global population (1.3 billion people) with less than 7% of the global arable land (130 million ha). This great accomplishment is ascribed to the agricultural revolution that started in 1978 and the application of mineral fertilizers. Before 1978, little P fertilizer was applied to the arable land, and P was mostly recycled from human excreta and back-yard livestock manure. However, the utilization of soil P by the crops was more than the total amount of P recycled from organic wastes, which resulted in a gradual decrease of soil fertility and crop yield. It has been estimated that there was 1.5 million tons of P deficit in the arable land from 1950 to 1960 (unpublished data). Since 1978, in rural areas a so-called “Household Responsibility System” was established to replace “the Big Commune”, which enormously stimulated the development of agricultural production in China (Tong et al., 2003). More diversified and productive, market-oriented farming systems replaced the traditional self-sufficient farming systems gradually. Farmers invested more than ever in the improvement of soil fertility to realize maximum crop harvests. With the increase of the labor costs and subsidized fertilizers, the majority of the richer farmers preferred mineral P fertilizers instead of collecting and recycling manure from their back-yards. Consequently, the separation of the crop production and livestock production systems interrupted the recycling loop, which is the prime cause of accumulated losses to the environment of up to 56% of animal manure P to the environment nowadays, especially in intensive animal production regions (Ma et al., 2012b).

1.2. The current situation of P application in China

The impressive current increase of crop productivity in agriculture compared with the 1970s is mostly the result of the large amount of P fertilizer input together with other production factors. Today China has become the largest consumer (30% of global total consumption) and producer (37.5% of global total production) of fertilizer P in the world (Wang et al., 2011; Zhang et al., 2008; Sattari et al., 2014). According to the International Fertilizer Industry Association (IFA) statistics, the total amount of mineral P fertilizer consumption in 2010 was 5.39 Tg, which was much more than the P harvested in crops (2.98 Tg, see

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Section 3.1.1). The surplus of mineral P fertilizer has built up phosphate reserves in the soil. For example, in North China Plain (NCP), the total P input was 92 kg ha^{-1} $year^{-1}$ compared with 39 kg ha^{-1} $year^{-1}$ of total P in agronomic output, resulting in as much as 53 kg P ha^{-1} $year^{-1}$ of surplus in the soil (Li et al., 2011b; Vitousek et al., 2009a). From 1980 to 2007, the average soil Olsen-P in the arable land has increased from 7.4 to 24.7 mg kg^{-1} due to an average 242 kg P ha^{-1} accumulated in soil in China during this period (Li et al., 2011b). The buildup of P in the arable land enhances the potential risk of P losses through surface runoff, soil erosion and leaching, which results in eutrophication of aquatic and terrestrial ecosystems (Fu et al., 2007; Sharpley, 1995; Sims, 1998; Chen and Chen, 2008; Vitousek et al., 2009b; Li et al., 2015a). Fu et al. (2007) showed that more than 60% of the major lakes and reservoirs were eutrophic because of high concentrations of total P and nitrogen (N) in water. Agricultural losses of P were identified as the dominant contributor to the total P losses according to the 1st National census of pollution sources in China (MOEP and MOA, 2010).

1.3. New challenges in the P flow chain

Over the last twenty years, China's economic development has shifted the diet of residents from plant-based to meat-enriched foods, which has stimulated a dramatic increase of livestock production, especially the intensive livestock production systems, and with that the manure production (Li et al., 2014). The annual growth of meat consumption was predicted to be 3.0% in China over the period 1997–2020 (Delgado et al., 2001). The intensive livestock production resulted for some regions in amounts of livestock manure P exceeding the P requirements of the crops, while still much mineral fertilizer P was, and is, used.

P in wastewater and domestic wastes, discharged without any treatment, is another threat to environmental quality (Li et al., 2011a). For example, in urban areas, the sanitation service system mixes human excreta and other wastewater streams, which results normally in a reduced reuse of P in excreta due to the potentially high level of heavy metals and other toxic wastes in industrial and non-residential wastewater (Cordell et al., 2009). In rural areas, the lack of the basic sanitary infrastructure leads to the direct discharge of the wastewater and wastes to the environment, which also causes serious deterioration of water quality in China (Chen et al., 2008).

Finally, though there is a huge reserve of phosphate rock in China, the main part of the reserve is low-grade, which is less efficient to mine and use and has a greater potential to pollute the environment because of more by-products of P discharged in purification processing (Wang et al., 2011). On the one hand, China is suffering from the depletion of its high-quality phosphate rock resource, and on the other hand the serious environmental pollution caused by the overuse of mineral P fertilizer, manure P losses and discharged P waste is a concern. Therefore, improving the P utilization and minimizing P losses to the environment through a better understanding of P flows and stocks in China's food chain is essential for identifying the key 'hotspots' and achieving P security. Given China's enormous share in global phosphorus production and consumption, it evidently plays a crucial role in developing a more sustainable use of this essential resource for agriculture.

1.4. The aim and method of analysis of this study

The aim of this paper is to present an integrated analysis of the P balance, PUE and the environmental implications at the national level of China, complemented with an analysis at regional, county and farm levels. These three sub-national levels provide additional insights in the underlying causes and spatial differences of P balances and PUE's to the study at the national level. We analyzed the P flows from phosphate rock mining to human consumption at multiple levels, and to our knowledge it is the first attempt to present a fairly comprehensive analysis of the entire P flow chain. The results from this study are essential to improve our understanding of P management for food security. Material Flow Analysis (MFA), also known as Substance Flow Analysis (SFA) was used to analyze the P balance, PUE and the environmental implications. MFA is a systematic approach that can be used to analyze the P flows into, out of and through a geographically defined system (Villalba et al., 2008). It has been used widely to analyze P flows at different levels, including the global level (Cordell et al., 2009; Liu et al., 2008), continental (Ott and Rechberger, 2012), national (Antikainen et al., 2005; Cordell et al., 2013; Wu et al., 2015a; Li et al., 2015b), regional (Belevi, 2002; Chen et al., 2009; Wu et al., 2015b), urban level (Aramaki and Thuy, 2010; Do-Thu et al., 2011) and farm level (Modin-Edman et al., 2007). We conclude with a discussion on possible policies and management measures at different levels to mitigate P use and emissions.

2. Materials and methods

2.1. Study area

Detailed information of P flows at national, regional, county and farm levels in China was obtained and analyzed by the static MFA approach. Because of data availability, the year 2010 was selected as the study year. At national level, Hongkong, Macao, and Taiwan were excluded because of lack of data, which had a minor influence on the P flows at national level due to the small agricultural production in these territories.

North China Plain (NCP) as one of the most important regions for the production of cereal crops in China was selected as the regional level. It is known as the Huang–Huai–Hai Plain because of the three major rivers that traverse it. The plain is located in the eastern coastal region of China, including Beijing, Tianjin, Hebei, Shandong, Henan, Anhui and Jiangsu provinces (Fig. 1). It produced approximately 42% of the country's total grain yield and consumed 40% of total mineral P fertilizer production in 2010. The net annual P surplus was 34 kg ha^{-1} in this region in 2010 (unpublished data). NCP has a continental monsoon climate, with an annual precipitation ranging from about 800 mm in the south to 500 mm in the north; the annual mean temperature is 14 ~ 15 °C. Soil is a moderately well-drained loamy soil with a deep profile (pH > 7.5).

Quzhou county in Hebei province was selected as an illustrative county. This county, located in the northwest of NCP, is a predominantly agricultural county. In 2010, the total administrative area was 66.7×10^3 ha, of which 72% was arable land. It has a semi-arid climate with annual precipitation of 790 mm and mean temperature of 14 ~ 15 °C. In the early 1980s, the salt-affected soils in the county were the main challenge to agricultural production. After significantly relieving the salt problem through the use of fresh water from deep wells for irrigation and deepening the drainage ditches to lower the groundwater table, crops still grew poorly on these soils with low organic matter and deficiencies of N and P (Liu et al., 2006). After 20 years of applying N and P fertilizers, the soil fertility and nutrient balance have changed dramatically. The average mineral P fertilizer used in Quzhou was 129 kg P per ha per year in 2010, much more than the crop actual demands, especially in vegetable greenhouse systems (SBQC, 2011).

Baizhai village, an important area of cereal crop production in Quzhou county, was chosen for farm level analysis. Investigation through questionnaires in 30 randomly selected farms in this village in July 2013 indicated that the field size varied from 0.2 to 2 ha with an average farm size of 0.47 ha. Three farms were then selected from the 30 surveyed farms for a detailed analysis as presented in this paper. Soil samples on these three farms were collected for soil P-tests (Section 3.3). Baizhai village and Quzhou county were chosen for farm level, village and county analysis in this study, because these were typical cereal production areas that went through an intensification process over the past decades. The China Agricultural University research group has cooperated with Quzhou county for over three decades and collected a lot of data.

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