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Research article

Nutrient-derived environmental impacts in Chinese agriculture during 1978–2015

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ABSTRACT

Nitrogen (N) and phosphorus (P) play a critical role in agricultural production and cause many environmental disturbances. By combing life cycle assessment (LCA) method with the mass balance principle of substance flow analysis (SFA), this study establishes a nutrient-derived environmental impact assessment (NEIA) model to analyze the environmental impacts caused by nutrient-containing substances of agricultural production in China during 1978–2015. The agricultural production system is composed of crop farming and livestock breeding, and the environmental impacts include energy consumption, global warming, acidification, and eutrophication. The results show all these environmental impacts had increased to $8.22*10^9$ GJ, $5.01*10^8$ t CO_2-eq, $2.41*10^7$ t SO_2-eq, and $7.18*10^7$ t PO_4^{3-}-eq, respectively. It is noted the energy consumption and the climate change caused by the crop farming were always higher than those from livestock breeding, which were average 60 and two times, respectively. While the acidification and the eutrophication were opposite after 1995 and 2000, even they were similar. This was mainly due to the high N application including synthetic N fertilizer (from $1.33*10^9$ GJ to $2.08*10^9$ GJ), applied manure (from $4.94*10^8$ GJ to $5.65*10^8$ GJ) and applied crop residue (from $2.94*10^8$ GJ to $5.30*10^9$ GJ), while the synthetic N fertilizer was controlled and the livestock expanded rapidly after 1995. Among the sub-categories, the three staple crops (rice, wheat, and maize) contributed greater environmental impacts, which were about two to 10 times as other crops and livestock, due to their high fertilizer uses, sown areas and harvests. While the oil crops and fruit consumed the least energies because of their much lower fertilizer-use intensities. Pig and poultry especially pig also caused obvious effects on environment (even 20 times as other livestock) because of their large quantities and excretions, which emitted much higher N_2O and P loss resulting in much higher climate change, acidification and eutrophication than other livestock. Then the study proposes the nutrient management in agricultural production by considering crop production, livestock breeding and dietary adjustment, so that some valuable experiences can be shared by the stakeholders in other Chinese regions.

1. Introduction

As a result of ongoing population growth and diet transition to meat consumption, the demand for crop- and animal-derived food has greatly increased during the last few decades. To support food security, agricultural production develops rapidly, which has also caused severe environmental problems, restricting agricultural development and food security in turn (Chen et al., 2014; Godfray et al., 2010; Vermeulen et al., 2012). This challenge may grow in the future, as global food demand is likely to double by 2050 cased by the population growth (Chen et al., 2014). As the largest developing country, China's agricultural production is essential and has greatly increased to support its economic growth and meet with the food demand of its large population. The increase rate of chemical fertilizer application had achieved to six times of crops (NBSC, 2016). Also, animal production has raised rapidly, mainly due to the Chinese dietary preference and increased imports of feed (Ma et al., 2012). However, the rapid development of Chinese

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agriculture also has brought many environmental pressures. For example, Chinese agriculture has consumed nearly 1/4 world's total agricultural energy, which correspondingly emitted annual GHG (greenhouse gas) emissions to over two times since 1978 (Fei and Lin, 2016; Luukkanen et al., 2015; Yu, 2016). The situation of growing contribution of agricultural sources to water quality degradation is now deteriorating even further (Chen et al., 2010). Thus, guaranteeing the increasing food needs while simultaneously reducing the environmental impact from agriculture is undoubtedly one of the greatest challenges of the century (Foley, 2011; Godfray et al., 2010; Makowski et al., 2014).

Nutrients such as nitrogen (N) and phosphorus (P) play a critical role in agricultural production and global food security (Erisman et al., 2008; Ma et al., 2012). They are contained in resources (eg. fertilizers, seed, and feed), products (eg. crops, meat, egg, and milk), and wastes (eg. crop residue, manure), flowing through the agricultural production including crop farming and livestock breeding (Chen et al., 2010; Fernandez-Mena et al., 2016). With the agricultural development, these nutrients flow quickly and massively. Large fractions of anthropogenically mobilized N losses through emissions of ammonia (NH_3), nitrous oxide (N_2O), and nitrogen oxide (NO_x). Also, large fractions of anthropogenically mobilized N and P flows into groundwater through runoff and leaching (Bouwman et al., 2013; Uwizeye et al., 2016). These have led to a series of environmental disturbances, including climate change, water eutrophication, and acidification (Fernandez-Mena et al., 2016; Sutton et al., 2013). For example, IPCC (2007) indicates agriculture currently accounts for approximately 14% of total global anthropogenic greenhouse gas emissions, and is responsible for about 58% of total anthropogenic emissions of N_2O. As the largest consumer of synthetic N in the world, Chinese agriculture has contributed 74% of the total N_2O emission in the country (NDRC, 2012). Fu et al. (2007) showed that more than 60% of the major lakes and reservoirs were eutrophic due to the high concentrations of total P and N in water. The 1st National census of pollution sources in China (MOEP and MOA, 2010) also identified the P loss from agricultural as the dominant contributor to the total P losses. It is therefore an urgent need to manage these nutrients to improve environmental performance in agriculture.

In fact, many studies have been published, focusing on the agricultural nutrient management. Earlier studies mainly evaluated nutrient inputs and outputs by using mass balance principle (Baker et al., 2001; Nilsson, 1995). They are believed to be appropriate for evaluating the nutrient flows and losses to determine the water eutrophication level. However, they treated systems as “black boxes”, which is difficult to identify sources of environmental impacts. Consequently, a systematic method named substance flow analysis (SFA) is proposed to improving nutrient management (Brunner, 2010). It is used to analyze flows and stocks of a single substance or of a coherent group of substances based on the mass balance principle (van der Voet, 2002). Concerning the importance of N and P in the social development, many SFA studies have examined nutrient flows at global (Canfield et al., 2010; Fowler et al., 2013; Chen and Graedel, 2016), national (Hamilton et al., 2017; Pearce and Chertow, 2017), regional (Asmala et al., 2011) and municipal (Thitanuwat et al., 2016) levels. China has also made great efforts to research nutrient flows. Liu (2004) and Chen and Chen, 2008 early analyzed P flows and P losses to water environment, providing the research basis of other related studies in China (Cui et al., 2013a; Wu et al., 2015; Gu et al., 2015; Liu et al., 2016). Apart from nutrient flow evaluation, Ma et al. (2013) and Wu et al. (2015) proposed improving the nutrient use efficiency in the food system of China. There are also many related studies especially in agricultural production and consumption in different regions, including watersheds (Asmala et al., 2011; Jiang and Yuan, 2015), provinces (Wu et al., 2014; Zhang et al., 2016a), and cities (Cui et al., 2015; Lin et al., 2016; Wu et al., 2012a). These studies examined nutrient flows systematically from the life-cycle aspect. However, emphasizing nutrient flow could only focus more on nutrient loss to surface water, while seldom consider other environmental impacts (e.g., energy consumption, climate change, land use, etc.). Thus, the SFA method cannot be solely implied to analyze the more varied environmental impacts and generate comprehensive recommendations.

Life cycle assessment (LCA) is a methodology to assess all the environmental impacts associated with a product, process or activity by identifying, quantifying and evaluating all the resources consumed, and all emissions and wastes released into the environment (Guinée, 2002). It is shown to be a systematic method analyzing the environmental impacts more comprehensively and more objectively (Wu et al., 2017). LCA method is mostly used in the industrial sector, such as energy (Garrido et al., 2017), building (Vitale et al., 2017; Wu et al., 2012b), and waste disposal (Nabavi-Pelesaraei et al., 2017). In recent years, LCA research began to pay more attentions on agriculture, and its derived environmental impacts (eg. climate change, acidification, eutrophication, etc.) (Foteinis and Chatzisymeon, 2016; Wu et al., 2016). Among these studies, the nutrients are also the research focus because of their key importance in agriculture (Ridoutt et al., 2013; Linderholm et al., 2012). While the nutrient-LCA studies are often conducted on some certain materials, such as fertilizers (Zhang et al., 2013; Hasler et al., 2015), crops (Zhang et al., 2016b), and wastes (ten Hoeve et al., 2014), or some certain sub-sectors, such as breeding (de Vries et al., 2015). They seldom consider the whole agricultural system composed of different agricultural activities (eg. cropping, breeding) and materials (eg. fertilizer, feed, nutrient leaching), which would provide more systematic analysis and comprehensive strategies. Moreover, the nutrient-based LCA is a more micro-method and some data are hardly collected or calculated directly, which would affect evaluating the environmental impacts. Consequently, combining the LCA method with the mass balance principle of SFA would be a more efficient method to analyze the nutrient-derived environmental impacts in the agriculture.

Here, this study analyzes the historical changes of environmental impacts derived by N and P in Chinese agricultural production system. The analysis consists of four parts: (a) establishing a model characterizing the nutrient-derived environmental impacts in agricultural production; (b) analyzing the environmental impacts caused by nutrients in the agricultural production of China during 1978–2015; (c) comparing the environmental impacts among the different crops and livestock; (d) proposing the nutrient management to mitigate the hotspots of these environmental impacts.

2. Methods

2.1. Logical framework of modeling

In this study, the environmental impacts in the agricultural production are quantified by using the nutrient-derived environmental impact assessment (NEIA) model. The model is established by combing LCA method with the mass balance principle of SFA. A schematic representation of the NEIA model is given in Fig. 1. Basing on the studies reviewed above, this study analyzes four environmental impacts including energy consumption, global warming, acidification, and eutrophication, which are mainly caused by the nutrient inputs and losses. Moreover, the agricultural production consists of crop farming and livestock breeding. Considering the great proportions of farming and breeding, nine crops (rice, wheat,