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Agricultural nitrogen and phosphorus emissions to water and their mitigation options in the Haihe Basin, China

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ABSTRACT

Agricultural nitrogen (N) and phosphorus (P) emissions to water bodies remain largely unknown in China, mainly due to the lack of reliable data sources and quantification tools. In this study, we constructed a grid-based NUFER (NUtrient Flow in food chains, Environment and Resources use) model in order to quantify a high-resolution agricultural N and P emissions to water bodies in Haihe Basin in 2012, based on data collected from county-level statistics, farm interview, and spatial data of topography, climate, soil texture, and land use. We also explored the mitigation strategies in 2030 via scenario analysis. The results showed that total agricultural N emission to water bodies in Haihe Basin was 1079 Gg N in 2012, of which cropland contributed 54%; total agricultural P emission to water bodies was 208 Gg P, livestock contributed 78%. There were large spatial variations in agricultural N and P emissions. Overall, the plain areas accounted for around 80% of the total agricultural N and P emissions to water in 2012. The highest N and P emission intensities were 10 t N km^{-2} and 2 t P km^{-2}, respectively. N and P emissions were significantly related to anthropogenic factors (such as the livestock density and cropland) in the plain areas; whereas in mountainous areas, both anthropogenic and natural factors (e.g., slope deviation and soil texture) significantly affected N and P emissions. Our scenario analysis suggests that agricultural N and P emissions can be reduced by up to 45% and 77%, respectively for N and P in 2030, via improved agricultural and environmental policies, technologies and managements. The prohibition of direct animal manure discharge to the water system seems to be the most effective measure to mitigate the emissions. Our study provided a high-resolution agricultural N and P emissions to the water bodies of Haihe Basin and identified the most effective options to reduce these emissions in highly intensified agricultural areas.

1. Introduction

Crop and livestock production has been intensified in China over the last decades. However, the nitrogen (N) and phosphorus (P) use efficiencies were relatively low due to sub-optimal management (Bai et al., 2013, 2014; Ma et al., 2013). Excessive N and P losses from agriculture have caused a series of environmental pollutions in China, such as $PM_{2.5}$ pollution (Wu et al., 2016), enhanced N deposition (Liu et al., 2013), groundwater quality degradation (Xue et al., 2009; Kaushal et al., 2011), and surface water eutrophication (Le et al., 2010; Strokal et al., 2016). Haihe Basin (HB), the most intensive agricultural production base in the Northern China, is facing serious air and water problems. For instance, annual mean $PM_{2.5}$ concentration in 2012 has reached 60 mg/m^3 (Zhao et al., 2017a), which imposes serious risks to the human health. The monitored groundwater nitrate-N concentration reached 113 mg/L (Zhang et al., 2004), significantly higher than the limit for nitrate in drinking water (50 mg/L) set by WHO and the EU (Zheng et al., 2015; Wang et al., 2017). The eutrophication and algal blooms often occurred in the surface waters (Zhang et al., 2015; Rong et al., 2016). In 2014, the surface water quality of nearly 50% of the monitored areas was graded as V or worse (i.e. the water can only be used for agricultural and other general purposes such as irrigating crops, trees and flowers in the cities, according to the Surface Water Environmental Quality Standard GB 3838-2002) (MEP, 2014). Intensive cropping systems and inefficient flood irrigation (Zhang et al., 2003a) further exacerbated the water pollution in this region. As yet, high-resolution agricultural N and P emissions to the water system of the HB are not available, which limit the exploration of efficient and

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effective mitigation options.

A quantitative understanding of agricultural nutrient emissions and their sources is key to mitigating emissions to water bodies. Many studies have attempted to address this issue via model simulations. For example, SWAT (the Soil and Water Assessment Tool) and AnnAGNPS (Annualized Agricultural Non-point Source Pollution Model) are the two popular models simulating watershed outputs from nonpoint and point nutrient sources (Baginska et al., 2003; Grizzetti et al., 2003). However, these models require large amount of detailed information, which constrains their application. Global *NEWS*-2 (Nutrient Export from WaterSheds) (Mayorga et al., 2010), a basin-scale model that requires fewer parameters, can be used to estimate N and P exports to rivers and seas worldwide, while the low spatial resolution and lack of current parameters limit its application. Recently, the NUFER model was used to quantify N and P losses from food chain to water bodies for China at national and provincial levels (Ma et al., 2010; Bai et al., 2016). As yet, agricultural N and P emissions to water bodies of the HB and their spatial patterns have not been systematically quantified, especially not in high resolution. The driving force of these spatial variations in the emissions has not been investigated. The lack of quantitative understanding limits the exploration of mitigation options and potentials.

Hence, the objectives of this study were (1) to quantify the N and P emissions from crop and livestock production systems to water system in the HB using the developed grid-based NUFER model; (2) to identify the driving factors for the spatial variations of N and P emissions; and (3) to explore effective mitigation options for reducing agricultural N and P emissions via the scenario analysis.

2. Material and methods

The Haihe Basin is located in the Northern China. It encompasses the two municipalities Beijing and Tianjin, most of Hebei Province, the eastern part of Shanxi Province, the northern parts of Henan and Shandong provinces, and small parts of Inner Mongolia and Liaoning Province (Fig. S1 in the Supplementary Information (SI)). It covers more than 300 counties, and is generally divided into fifteen sub-basins (Seen Fig. 3). The total area of the HB is 3.2×10^5 km^2, feeding 11% of the national population, and contributing 14% of China's total gross domestic production (GDP) in 2012. The HB is an important base for agricultural production. It provided 10% of grain yield, 20% of milk, 10% of meat, and 21% of eggs in China in 2012, according to the Statistical Yearbooks of individual provinces or some prefectures. We did not include the contributions of small parts from Inner Mongolia and Liaoning Province because their contributions to the agricultural production were marginal, compared to the other major parts of the HB.

Agricultural N and P emissions to water include emissions from cropland and livestock farms, mainly via surface runoff, erosion, and leaching or direct manure discharge. To quantify the N and P emissions to water, we constructed a grid-based NUFER model, based on Ma et al. (2010) and Bai et al. (2016). The main improvements in the grid-based NUFER model were following (1) the model considered detailed chemical fertilizer types (urea, ammonium bicarbonate, ammonium nitrate, ammonium sulfate, diammonium phosphate, compound fertilizer, and other), fertilization methods (basal and top dressing), and livestock manure management systems (liquid and solid subsystems for dairy cattle, beef cattle, and pig farms), based on a comprehensive farm interview covering 400 individual farms in 11 typical counties in the HB (Zhao et al., 2017b); (2) the model could quantify the N and P emissions to water in high resolution, via estimating gridded emission parameters.

2.1. Estimates of agricultural N and P emissions to water system

2.1.1. N and P emissions from arable land

(1) N and P emissions via surface runoff

$$N, P_{runoff} = N, P_{Application} \times SRF_{max} \times flu \times min(fp, frc, fs) \quad (1)$$

Where, N,P_{runoff} is the estimated total agricultural N/P emission to water via surface runoff, unit: t; $N,P_{Application}$ is N/P applied to arable lands, including animal manure N/P application, unit: t. SRF_{max} is a maximal surface runoff fraction, flu, fp, frc, fs are the reduction factors for land use, precipitation, soil depth, and soil type, respectively.

(2) N and P emissions via erosion

$$N, P_{erosion} = N, P_{topsoil} \times EF_{erosion,max} \times fp \times min(flu, frc, fs) \quad (2)$$

Where, $N,P_{erosion}$ is the estimated total agricultural N/P emission to water via erosion, unit: t; $N,P_{topsoil}$ is the total N/P content in topsoil, unit: t. EF_{max} is a maximal erosion fraction. Other parameters are the same as those in Eq. (1).

(3) N and P emissions via leaching

$$N, P_{leaching} = N, P_{surplus} \times LF_{soil\ type,max} \times flu \times min(fp, frc, ft, fc) \quad (3)$$

Where, $N,P_{leaching}$ is the estimated total agricultural N/P emission to water via leaching, unit: t; $N,P_{surplus}$ is the N/P surplus on the soil surface N/P balance, unit: t. LF_{max} is the maximal leaching fraction. ft and fc are the reduction factors for temperature and soil organic matter content, respectively. Other parameters are the same as those in Eq. (1).

2.1.2. N and P emissions from livestock farms

N and P emissions to water from livestock farms were mainly via direct discharge, erosion, and leaching from housing, storage, and treatment stages in livestock manure management chain. N or P excretion was calculated by multiplying N or P excretion rates (Table S1) with the livestock number in different livestock systems. N or P emission was calculated as the results that manure N or P in each stage multiples the corresponding emission factors.

All the parameters could be found in Table S1-S4 in the SI.

2.1.3. Estimation of gridded N and P emissions

For the crop production system, we first estimated the grid emission parameters at 1 km × 1 km spatial resolution (Fig. 1) based on the algorithm in 2.1.1 and spatial distribution of topography, soil texture, annual mean temperature, annual precipitation, and land use. The data of topography, soil texture, and land use were provided by the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (RESDC) (http://www.resdc.cn), annual mean temperature and annual precipitation were estimated via spatial interpolation methods applied by RESDC (Fig. S2). The N/P application, N/P in the topsoil, and N/P surplus were then evenly allocated to the arable areas in each county based on the land-use map at 1 km × 1 km spatial resolution (Zhao et al., 2017a). Finally, the N and P emissions to the water system were calculated using the previous spatial emission parameters and activity data.

For the livestock production system, we evenly distributed the N and P emissions from housing, storage, and treatment stages to the rural settlement areas in each county based on the land-use map (Zhao et al., 2017a).

2.2. Data collection

Data sources included county-level agricultural N and P associated activity data for 2012, parameters, and spatial data. Agricultural N and P associated activity data were derived from a variety of local statistical yearbooks. These activity data included population, rural income, the cultivated area, the sown area of each crop, animal numbers, agricultural inputs such as the amount of chemical fertilizer application, and crop and livestock products. The parameters, such as the N and P contents of chemical fertilizers and products, the application rate of each crop-specific chemical fertilizer, and livestock manure