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National-scale evaluation of phosphorus emissions and the related water-quality risk hotspots accompanied by increased agricultural production

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ABSTRACT

Water quality and food security are two key themes of human existence, and the critical question we are facing is how to achieve safe water quality without decreasing agricultural production. In this study, an assessment framework has been developed by scaling emission factors from 232 monitoring plots to large scales, as well as by introducing two new concepts, agriculture-water body transportation potential (AWP) and crop-environment partition coefficient (C/E) values. Then, a first assessment of national-scale agricultural non-point-source phosphorus (NPS-P) emissions and the related water-quality risk during Chinese agricultural miracle period were provided at high resolution (1 km*1 km). Finally, a joint analysis of the national NPS-P emissions and crop production hotspots was conducted in support of sustainable development on a national scale. The results indicated that NPS-P emissions from agricultural fertilizer application in China have increased by 31% from 2004 to 2013, but high- and extremely-high-risk areas of agricultural pollution have decreased by 38%. The Lianghu Plain, North China Plain, and Yangtze River Delta were identified as hotspots of high crop yields, while an improvement in nutrient utilization in terms of increasing C/E values in these regions could also be observed.

1. Introduction

As the key element in all living systems, phosphorus (P) has been widely recognized as the global cause of eutrophication of water bodies (Faridmarandi and Naja, 2014; Foy et al., 1995; Oenema et al., 2005). Farmland constitutes the world's largest terrestrial biome, and agricultural expansion has led to a 35–40% increase in fertilizer application worldwide during recent decades, leading to an estimated 25.7% of global P emissions (Smith et al., 1999; Vitousek et al., 2009). For thousands of years, the most important scientific and political question we have faced is how to achieve safe water quality without compromising food security and a standard of living, as these two objectives often compete with each other (Matson et al., 1997).

Previous studies have reported that the majority of agricultural P emissions are driven by storm events and delivered via overland flow as non-point source (NPS) pollution (Chen et al., 2017, 2014). To date, the recognition of the impacts of agricultural fertilizer application on aquatic systems has driven observational networks at plot and catchment scales, as well as the funding of models and remote sensing to expand studies to regional, national, and even global scales (Caires et al., 2017; Ju et al., 2009). However, considerable uncertainty remains in our knowledge of the sources, magnitude, and spatial-temporal changes of agriculture non-point-source phosphorus (NPS-P) emissions, especially for large-scale regions (Chen et al., 2016). In comparison, more attention has been paid to agricultural nitrogen (N) instead of P due to differences in the agronomic efficiency, and complexities of transportation processes, as well as inadequate analytical methods (Gao et al., 2017). However, recent studies have noted that the control of N fertilizer might exacerbate soil P enrichment in farmland, which would lead to even more serious water quality problems. One challenge for current research is to improve our understanding of agriculture NPS-P emissions by scaling up findings from a relatively small number of well-studied plots or catchments and extrapolating these results to entire regions or countries, which has been identified as a bottom-up framework (Ma et al., 2012). Other large-scale studies have also been performed based on the mass-balance approach from the bottom-up perspective, while the nutrient flux between each subsystem, including the agricultural, urban, forest, and other systems, is calculated (Gu et al., 2015). For example, Gu et al. (2015) put forward the whole N budget in China in order to estimate the reactive N balance

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among seven important subsystems. Similarly, Rochette et al. (2018) estimated the nitrous oxide from agricultural soil in Canada using a unique fertilizer-induced emission factor. However, it should be noted that these methods are not detailed enough as these nutrient fluxes are often estimated using specific fixed emission factors due to data availability. These fixed emission factors might be questionable because they could not reflect discrepancies of topography, climate, and cropping patterns on a large scale, where heterogeneity did exist and would impact the NPS-P emissions (Chen et al., 2018). In addition, the quantification of agricultural NPS-P emission is of particular interest globally but predicting fertilizer P emissions into nearby water bodies is even more challenging at a large scale. Previous remote sensing and modeling-based studies have suggested that variations in fertilizer NPS-P problems and the related water-quality risks are determined by both the source conditions and transportation patterns, which would be regulated by many different influencing factors, such as the distance from the river, slope and vegetation cover (Kaushal et al., 2011). Heckrath et al. (2008) utilized a P index method to identify the high-risk areas of NPS-P emissions to the nearby water bodies in Nordic catchments, but the results are qualitative, and national-scale quantitative studies have not yet been conducted.

China is home to one-fifth of the word population (approaching 1.4×10^9 people), and has followed its own agricultural growth trajectory (Ouyang et al., 2017). It has witnessed an agricultural miracle by increasing the crop production from 1.2×10^9 tonnes to 1.7×10^9 tonnes from 2004 to 2015 (FAO, 2015). However, to some extent, China has become a global hotspot of agricultural NPS-P problems. Although some aspects of P cycling in China have been studied from plot-based monitoring to catchment-based simulation at farm or catchment scales (Adams et al., 2016; Kyllmar et al., 2014), large uncertainties and even contradictory results were found in terms of spatial and temporal variations in agricultural NPS-P emissions and their water-quality risks due to different climatic conditions, soil types, hydrology and farming systems (Chen et al., 2016; Zhu et al., 2011). In addition, due to the lack of analytical methods, previous studies did not clearly define the relationship between crop production and the consequent NPS-P emissions to nearby water bodies.

Our overall objectives are to: 1) develop a novel assessment methodology for agricultural NPS-P emissions and environmental fates on a national scale; 2) conduct the first national-scale assessment of the spatial-temporal variation in agricultural NPS-P emissions and the related water-quality risk during Chinese agricultural miracle period; 3) advance our understanding of this subject by a joint analysis of national crop production and NPS-P emission hotspots to support sustainable development on a national scale.

2. Materials and methods

2.1. Definition of the system boundary and data sets

The study area covered the entire land area of mainland China, while Taiwan, Hong Kong, and Macao and part of Hainan province were excluded due to limitations with regard to the data available from these regions. Input data in this study were collected from various public sources and complied as two categories: statistical data and spatial data. Specifically, statistical data, such as the amount of fertilizer application, sowing area, and crop yields for cereal, vegetables and other crop types, were derived from the national data center (NBSC, 2015), as well as provincial and municipal statistical yearbooks. These, data compose their own database as a result of compiling all information from the 341 municipal administrative units. Specifically, some scarce data points were generated by the interpolation method and regionalization method, which are described in Section 1, Appendix A. In addition, spatial data such as digital elevation maps (DEM), land use data, river networks, and the normalized difference vegetation index (NDVI) at the resolution of 1 km*1 km, were obtained from the Data Center for Resources and Environmental Sciences, Chinese Academy of Science (REDCP, 2013). Details about the input data are found in Table A.1.

To cover Chinese agricultural miracle period from 2004 to 2015, the three typical years of 2004, 2008 and 2013 were selected for NPS-P emission calculation for the following reasons. First, the major strategies for increasing Chinese crop production were established in 2004 and revised every five years through the Chinese National Five-Year-Plan (Kang et al., 2016), it is also the first year in food crop production increased for the 12th year in a row. Then, the Chinese government published the first investigation results of the national agricultural pollution source census in 2008, which could be used for comparison with our results. Finally, 2013 was also selected because data availability of last year. The annual precipitations range 14.3–2171.5 mm, 20.3–2962.2 mm, 7.1–2859.6 mm among China for 2004, 2008 and 2013, respectively, and the spatial distribution of annual precipitation and NDVI is shown in the Fig. A.1(a) and (b).

2.2. Quantification of agricultural NPS-P emissions

The flow chart of the new assessment methodology is shown in Fig. A.2, which comprises the three major steps of quantification of agricultural NPS-P emissions, a subsequent calculation of the related water-quality risk, and a final joint analysis of crop production and NPS-P emission hotspots. First, the annual NPS-P emissions from agricultural fertilizer application were calculated based on specific emission factors that were derived from 232 standard monitoring sites throughout China, which were built by the Chinese government at least 8 years before the First pollution-source census. These specific emission factors have been previously published and publicly available in Agricultural Source Coefficient Handbook (Ren et al., 2015). For each monitoring site, a standard overflow-collecting pool and accompanying analytical instrumentation have been setup, while strict data quality control and periodic expert checks have been performed to provide the systematic measurement of agricultural NPS-P at the national scale. By considering the background emission, measurements were designed as two parallel treatments: the baseline scenario was designed as the control treatment with no fertilizer applied in the plot; the fertilizer application scenario was designed based on extensive investigation of local fertilizer amounts, the fertilizer application method and application time in accordance with the production habits of the local farmers. Following state regulations, six sampling areas were set up with identical areas (no less than 20 m^2), shapes and specifications, and at least three replications were required during every treatment. The monitoring covered the entire crop growth period, and the annual emission factors for agricultural fertilizer application were obtained as the proportion of the NPS-P emissions relative to the total fertilizer application for a specific cropping pattern. For each monitoring plot, the NPS-P emissions were calculated based on the following equation:

$$RL = \sum_{i=1}^{n} c_i \times V_i \tag{1}$$

where RL is the P emissions during the fertilizer application scenario (kg km^{-2}); c_i and Vi is measured P concentration and volume of the i_{th} surface runoff; i represents the number of rainfall events during the monitoring period.

Then, the emission factor for agricultural fertilizer application is calculated by quantifying the differences in NPS-P emissions between these parallel treatments. The equation for the emission factor is shown as follows:

$$\mu = \frac{RL - CK}{FA} \times 100\% \tag{2}$$

where μ is the emission factor in a certain field; CK is the amount of P emissions during the baseline scenario (kg km^{-2}); and FA is the