

Hotspots for Nitrogen and Phosphorus Losses from Food Production in China: A County-Scale Analysis

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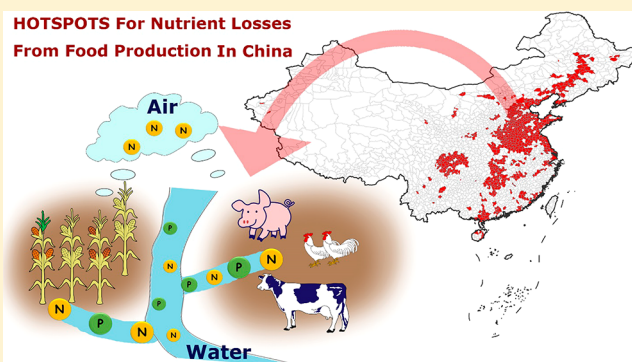
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S Supporting Information

ABSTRACT: Food production in China results in large losses of nitrogen (N) and phosphorus (P) to the environment. Our objective is to identify hotspots for N and P losses to the environment from food production in China at the county scale. To do this, we used the *NUFER* (Nutrient flows in Food chains, Environment and Resources use) model. Between 1990 and 2012, the hotspot area expanded by a factor of 3 for N, and 24 for P. In 2012 most hotspots were found in the North China Plain. Hotspots covered less than 10% of the Chinese land area, but contributed by more than half to N and P losses to the environment. Direct discharge of animal manure to rivers was an important cause of N and P losses. Food production was found to be more intensive in hotspots than in other counties. Synthetic fertilizer use and animal numbers in hotspots were a factor of 4–5 higher than in other counties in 2012. Also the number of people working in food production and the incomes of farmers are higher in hotspots than in other counties. This study concludes with suggestions for region-specific pollution control technologies for food production in China.



INTRODUCTION

Nitrogen (N) and phosphorus (P) applications in food production greatly contribute to global food security as essential nutrients for the growth of plants and animals. However, this can also lead to N and P losses to the environment.^{1–6} Increasing losses of N and P to surface waters and the atmosphere have negative impacts on ecosystems and biodiversity. For example, increased N and P losses from food production may cause eutrophication and harmful algae blooms in many coastal areas around the world.^{7–11}

N and P losses from food production including crop and animal production in China have been increasing since the 1980s.^{12–16} Ma et al.¹⁷ estimated that total P losses from crop production in 2005 were 300% higher than that in 1980, while from animal production P losses were more than 42 times as high as that in 1980 in China. This implies that an increasing amount of nutrients was lost to air and waters.^{4,9,18–21} Various studies discussed the reasons why nutrient losses in China are high and increasing.^{4,9,19,21–25} An important reason is poor nutrient management technologies in food production: overuse of synthetic fertilizers and animal feeds, low productivity, and poor management of animal manure. However, most existing analyses are limited to the national or provincial levels, and they

often do not discuss the possible relations between nutrient losses and socio-economic conditions that are usually the drivers of intensive food production in China.^{22,24–27} A more detailed analysis of N and P losses from food production at, for instance, the county scale does not exist. Such an analysis is highly relevant because it can provide more explicit quantitative information on N and P flows in food production in China. The result will contribute to identifying the “hotspots” where N and P losses from food production are higher than other regions. Analyzing the N and P flows in the hotspots and local agricultural and socio-economic indicators may help to develop region-specific nutrient management technologies and policies to reduce the potential for nutrient pollution in China.

Thus, our study aims to identify hotspots for N and P losses to the environment from food production in China at the county scale. To do this, we used the *NUFER*²⁸ (Nutrient flows in Food chains, Environment, and Resources use) model. We analyzed N and P losses from food production including crop

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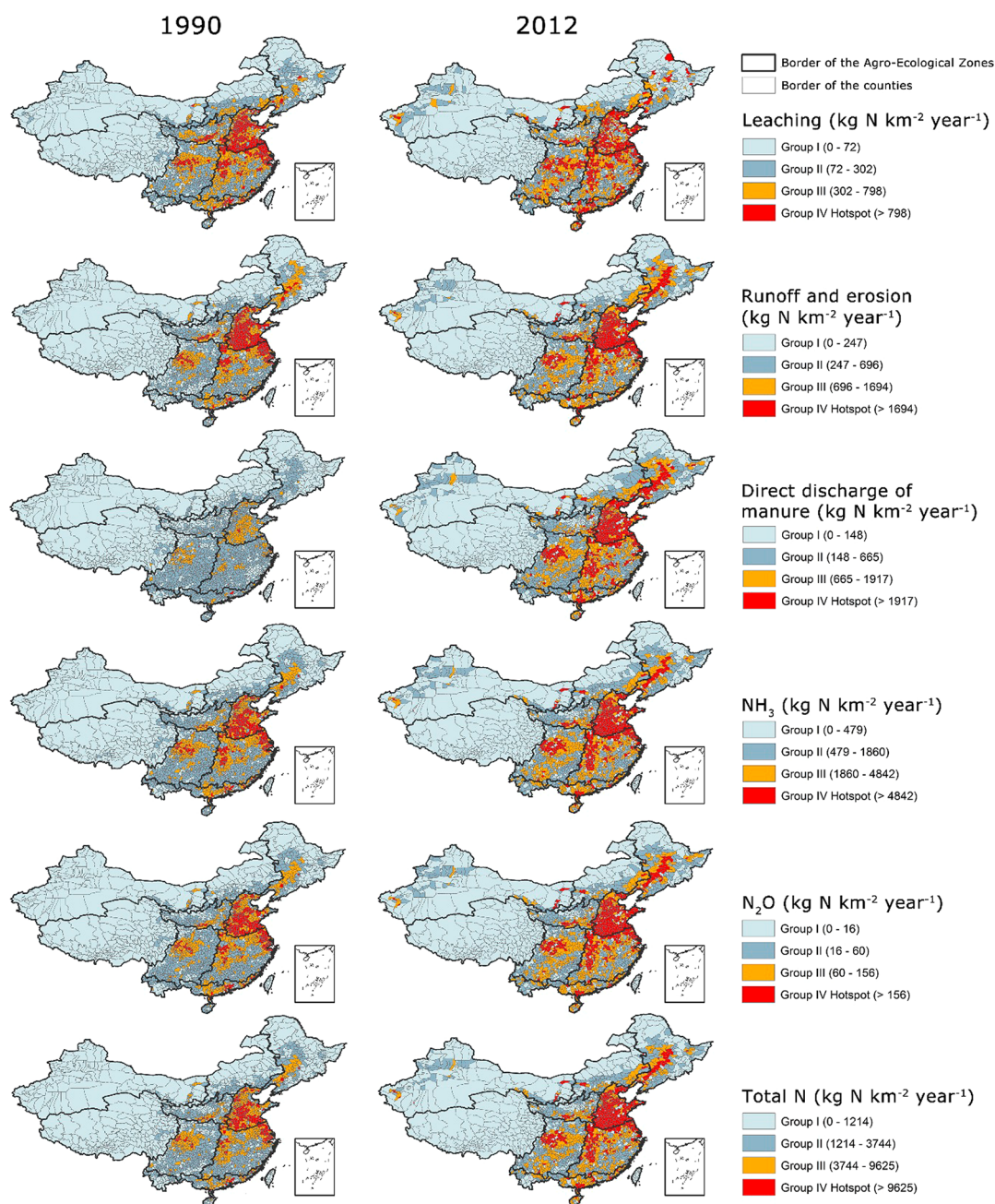


Figure 1. Nitrogen (N) losses (kg N km⁻² year⁻¹) to the air and waters from leaching, runoff, and erosion, direct discharge of manure, ammonia (NH₃), and nitrous oxide (N₂O) emissions, and the total N losses (kg N km⁻² year⁻¹) from food production in 1990 and 2012. The N losses were quantified using the *NUFER* model. The intervals for the four groups in this figure were defined based on quantiles (25%, 50%, 75%) of N losses of all counties in 2012: group I (0–25%), group II (25–50%), group III (50–75%), group IV (75–100%). Counties in group IV were qualified as hotspots. The same information for 2000 is available in [Figure S2](#). The names of the Agro-Ecological Zones are available in [Figure S8](#).

and animal production for all Chinese counties in 1990, 2000, and 2012. We also quantified the associated N and P use efficiencies of food production in China to better understand the high losses in the hotspots. We compared several agricultural and socio-economic indicators for the hotspots with that for other counties in 2012. On the basis of the results, we conclude with suggestions on technologies and policies for nutrient pollution control in food production of China.

MATERIALS AND METHODS

NUFER Model. In this study we used the *NUFER*^{17,28} model to quantify N and P losses from food production for all

counties in China for 1990, 2000, and 2012. Food production includes crop and animal production in this study (Figure S1 in [Supporting Information](#)). Years 1990, 2000, and 2012 were selected to reflect the period during which the transition of food production in agriculture from traditional small scale to intensive large scale took place in China (see section S1 in the [Supporting Information](#) for more information about the transition). The original *NUFER* model was developed by Ma et al.²⁸ to quantify N and P flows in the food production, processing and consumption chain of China using a mass balance approach. This model calculates nutrient flows at the national level for each year from 1980 to 2010, and for the year

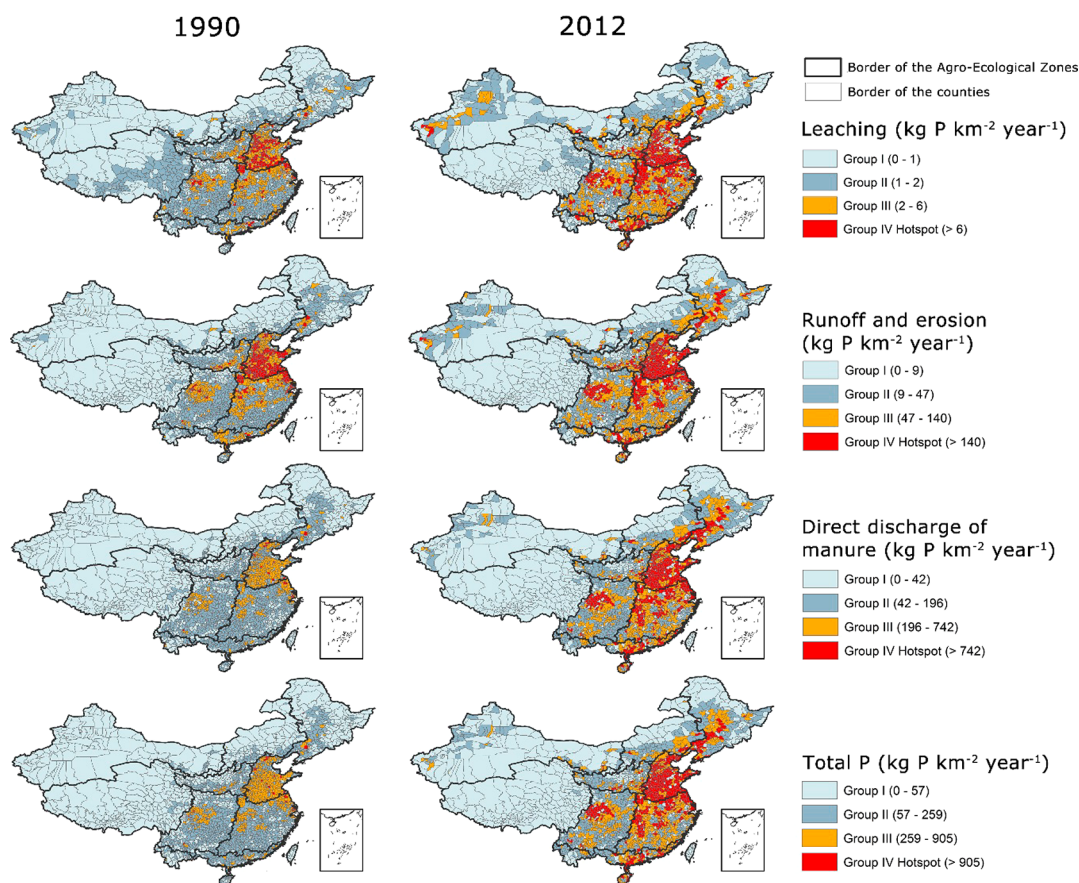


Figure 2. Phosphorus (P) losses ($\text{kg P km}^{-2} \text{ year}^{-1}$) to waters from leaching, runoff and erosion, direct discharge of manure, and the total P losses ($\text{kg P km}^{-2} \text{ year}^{-1}$) from food production in 1990 and 2012. The P losses were quantified using the *NUFER* model. The intervals for the four groups in this figure were defined based on quantiles (25%, 50%, 75%) of P losses of all counties in 2012: group I (0–25%), group II (25–50%), group III (50–75%), group IV (75–100%). Counties in group IV were qualified as hotspots. The same information for 2000 is available in Figure S3. The names of the Agro-Ecological Zones are available in Figure S8.

2030. In addition, regional nutrient flows can be calculated for 31 provinces for 2005 and 2013. Detailed model description on the original *NUFER* model is available in section S2 in the Supporting Information. We developed and applied *NUFER* for all Chinese counties using county information,²⁹ which was not done before. We also improved *NUFER* by including dry atmospheric N deposition on arable land that was not included in the original model. We described in section S2 in the Supporting Information how we included dry atmospheric N deposition and applied *NUFER* to the county scale.

Identifying Hotspots. We quantified the N and P losses to waters and the air from food production including crop and animal production systems using *NUFER*. The losses to waters are the N and P losses from leaching, surface runoff, and erosion in crop production, and N and P losses from direct discharge of animal manure in animal production. For the losses to the air, we calculated the emissions of ammonia (NH_3) and nitrous oxide (N_2O) from crop and animal production systems. The details in the calculation of N and P losses using *NUFER* are available in section S2 in the Supporting Information. The calculated N and P losses in all counties were averaged by the area of the counties and were grouped into four groups (Figures 1 and 2). The intervals for the four groups were defined based on quantiles (25%, 50%, 75%) of the averaged N and P losses of all counties in 2012: group I (0–25%), group II (25–50%), group III (50–75%), group IV (75–100%, hotspot). The top 25% were considered

hotspots. For 1990, 2000, and 2012 counties were considered as hotspots if their N and P losses fall within the range of the top 25% for 2012. Thus, for all three years counties that have total N losses exceeding $9625 \text{ kg N km}^{-2} \text{ year}^{-1}$ were qualified as hotspots (Figures 1 and S2). For P, counties with total losses of more than $905 \text{ kg P km}^{-2} \text{ year}^{-1}$ were qualified as hotspots (Figures 2 and S3). We did not identify hotspots based on water or air quality standards in China, because these standards differ among regions (e.g., provinces) and the use of the water body. For example, the water quality standards for drinking water supply differ from standards for water that are used for agricultural purposes. Therefore, we used the top 25% for 2012 as a basis for the identification of hotspots as shown in Figures 1 and 2. We also calculated the associated N and P use efficiencies of food production for a better understanding of N and P losses. N and P use efficiencies were calculated as outputs of N and P via main products divided by the total inputs of N and P to this system (Box S3).

We included in our result (Figures 1, 2, S2, and S3) borders of the nine Agro-Ecological Zones (AEZs) in China to illustrate the spatial distribution of the hotspots for N and P losses. The AEZs are Northeast China, Inner Mongolia and Great Wall Vicinity, North China Plain, Loess Plateau, Middle and Lower Yangtze River, Southwest China, South China, Gansu and Xinjiang, and Tibetan Plateau (see Figure S8 for the location of the AEZs). These zones were defined by Sun and Shen³⁰ based on their similarities in crop production (e.g., crop land, crop

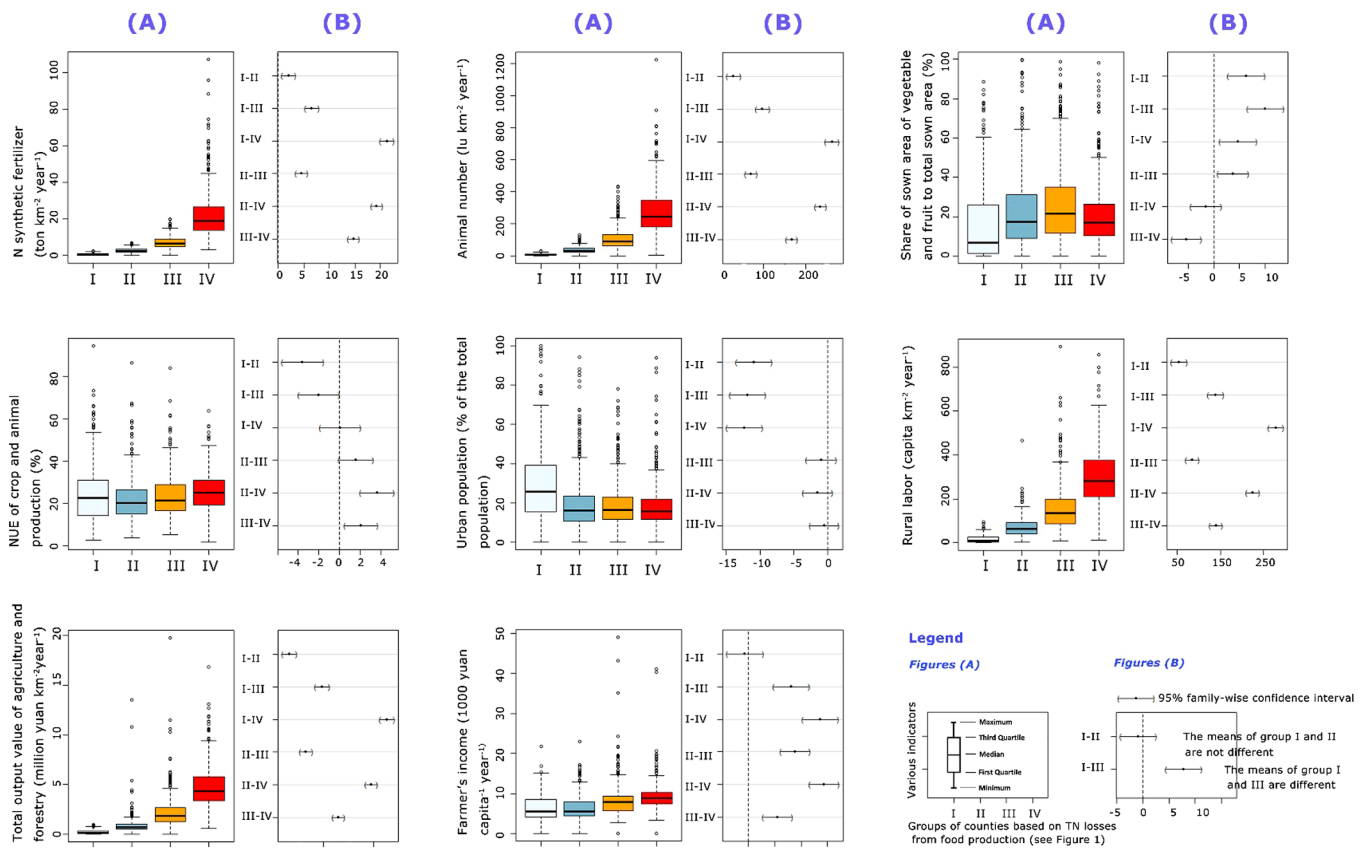


Figure 3. Boxplots for nitrogen (N): synthetic fertilizer ($\text{ton km}^{-2} \text{year}^{-1}$), animal number in livestock unit ($\text{lu km}^{-2} \text{year}^{-1}$, see Supporting Information for converting animal numbers in livestock unit), share of sown area of vegetable and fruit to the total sown area (%), N use efficiency (NUE) of food production, urban population (% of the total population), rural labor ($\text{capita km}^{-2} \text{year}^{-1}$), total output value of agriculture and forestry (billion yuan $\text{km}^{-2} \text{year}^{-1}$), and farmers' incomes ($1000 \text{ yuan capita}^{-1} \text{year}^{-1}$) among the four groups of total N losses (see Figure 1) in 2012 (A), and the pairwise comparisons from Tukey's Honest Significant Difference (Tukey's HSD) among the four groups (B). In B panels any 95% confidence intervals that do not contain 0 provide evidence of a difference in the groups.

types) and animal production (e.g., animal type, animal numbers) systems.

Comparing Agricultural and Socio-economic Indicators in Hotspots with Nonhotspots. We compared several agricultural and socio-economic indicators in hotspots (group IV in Figures 1 and 2, and in Figures S2 and S3) and nonhotspot counties (groups I, II, III in Figures 1 and 2, and in Figures S2 and S3) in 1990 and 2012. The agricultural indicators are (i) N and P inputs to cropland from synthetic fertilizer, (ii) animal numbers, (iii) share of sown area of vegetable and fruit to total sown area, and (iv) N and P use efficiencies of food production including crop and animal production. The socio-economic indicators are (i) urban population, (ii) rural labor, (iii) total output value of agriculture and forestry, and (iv) farmers' incomes. We selected all socio-economic indicators that are available in county statistics. The Tukey's Honest Significant Difference (Tukey's HSD) method was used to make pairwise comparisons of the agricultural and socio-economic indicators among the groups I, II, III, and IV that was defined above. The results of Tukey's HSD comparison are shown in Figures 3 and 4, and in Figures S4 and S5.

RESULTS

Hotspots for N and P Losses. The N and P losses increased fast between 1990 and 2012. As a result, the hotspot

area in China expanded during this period. The hotspot area for total N losses increased by a factor of 3 (from 307 850 to 828 205 km^2), and for total P by a factor of 24 (from 35 355 to 861 781 km^2) between 1990 and 2012 (Table S6). The hotspots covered less than 5% of total land and contributed to 28% of total N losses, and 10% of total P losses in food production of China in 1990. In 2012, the hotspot area for total N and total P losses expanded to 9% of the total land in China. Astoundingly, these hotspots contributed more than half of nutrient losses (52% of total N losses, and 62% of total P losses) in this year. The increase in hotspot area and in contributions to total losses in China by hotspots are also calculated for N and P losses from various sources in Figures 1 and 2 and Table S6.

The spatial distribution of hotspots also changed between 1990 and 2012. In 1990, most hotspots are found in the North China Plain, and in the northeastern part of the Middle and Lower Yangtze River (Figures 1 and 2). In 2012, the hotspots expanded to cover a larger area of the North China Plain. Some counties in the AEZs Middle and Lower Yangtze River, Northeast China, Loess Plateau, Southwest China, and South China also show high N and P losses as hotspots. In the AEZs where the hotspot areas expanded, the food production is intensive and increased fast between 1990 and 2012 (Figure S9). The nonhotspots with low N and P losses (groups I and II in Figures 1 and 2) are found across northern and western

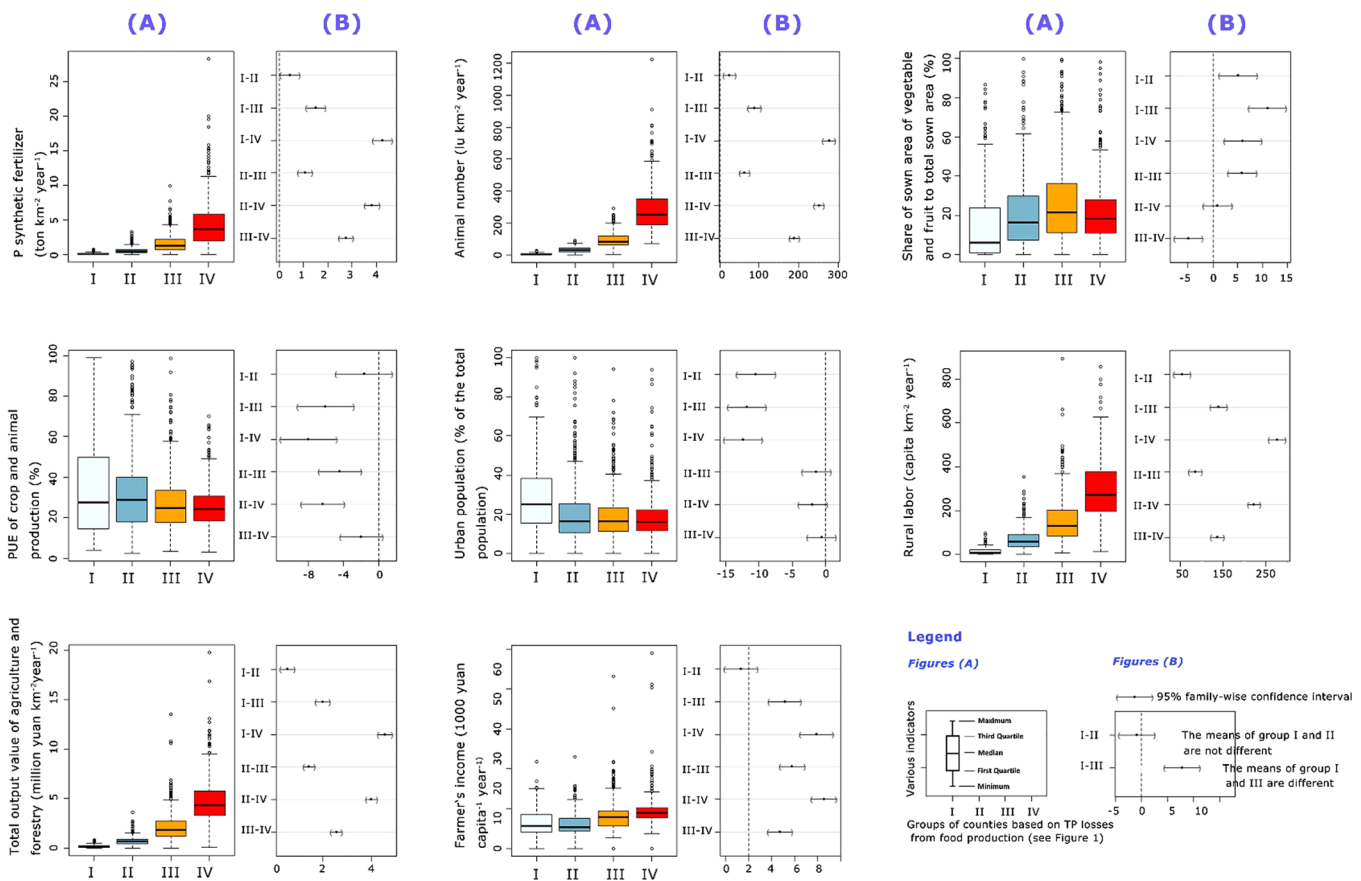


Figure 4. Boxplots of for phosphorus (P): synthetic fertilizer ($\text{ton km}^{-2} \text{year}^{-1}$), animal number in livestock unit ($\text{lu km}^{-2} \text{year}^{-1}$, see Supporting Information for converting animal numbers in livestock unit), share of sown area of vegetable and fruit to the total sown area (%), P use efficiency (PUE) of food production, urban population (% of the total population), rural labor ($\text{capita km}^{-2} \text{year}^{-1}$), total output value of agriculture and forestry ($\text{billion yuan km}^{-2} \text{year}^{-1}$), and farmers' incomes ($1000 \text{ yuan capita}^{-1} \text{year}^{-1}$) among the four groups of total P losses (see Figure 2) in 2012 (A), and the pairwise comparisons from Tukey's Honest Significant Difference (Tukey's HSD) among the four groups (B). In B panels any 95% confidence intervals that do not contain 0 provide evidence of a difference in the groups.

China in 2012, for example, in AEZs Inner Mongolia and Great Wall Vicinity, Gansu and Xinjiang, and Tibetan Plateau where food production is less intensive (Figure S9).

The result also shows that direct discharge of animal manure to waters in the hotspots became a more important source of N and P losses in food production over the last 30 years. In 1990, the hotspots for N and P losses to waters from direct discharge of manure only covered 0.2% and 0.3% of the total land. These hotspots were responsible for less than 10% of the total N and P losses from discharge of manure (Table S6). However, in 2012 the hotspots area for direct discharge of manure is calculated to increase by a factor of 51 for N losses and of 33 for P losses comparing to 1990. And these hotspots contributed to more than half of N and P losses (57% for N and 64% for P) from direct discharge of manure in China (Table S6). This change in N and P losses from direct discharge of animal manure could be related to the transition of food production in China started in 1990s (section S1, Figures S6 and S7).^{31,32} Traditional-oriented food production was dominant in the 1990s. Traditional animal systems are small in size and combined with crop production. Animal manure is usually used as organic fertilizers for crops. Therefore, the discharge of manure to waters is relatively low.^{33–35} Industrial, highly intensive systems dominate food production in China since 2000s. Industrial animal production systems are large in size and are separated from crop production. The animal manure is

usually collected, and discharged to surface waters or landfills without treatment.^{26,31,33–35} Therefore, the discharge of manure to waters has been increasing since 2000 particularly in the counties that have intensive animal production activities. Our results in Figures S6 and S7 indicate that intensive animal production in the hotspots is considerably higher than that in nonhotspot counties ($P < 0.05$). This situation lasted at least until the 'Regulation on the Prevention and Control of Pollution from Large-Scale Breeding of Livestock and Poultry' was introduced by Chinese Premier Li,³⁶ and implemented since 1 January 2014. By introducing this policy, the Chinese government aims to improve manure management and manure recycling in order to reduce the environmental pollution caused by intensive animal production. The "Livestock and Poultry Manure Utilization Action Program (2017–2020)" was introduced by MOA³⁷ in late 2017. As a result, the direct discharge of animal manure may become smaller in the future. Our results present the situation in 2012, when policies on manure management were not widely introduced and not very effective.

Agricultural and Socio-economic Indicators. Comparing the hotspots with nonhotspot counties shows that food production in the hotspots was more intensive than in other counties (Figures 3 and 4, Figures S4 and S5, $P < 0.05$) in both past (1990) and recent (2012) years. The mean synthetic fertilizer use and mean animal numbers in the hotspots were

Table 1. Comparison of N and P Losses (Tg year⁻¹) to the Air and Waters from Food Production Including Crop and Animal Production in China by Our Study with Estimates by Other Published Studies

N or P losses (Tg year ⁻¹)	studies	system boundary	2000	2006	2007	2008	2010	2012
NH ₃	This study	food production	11.3					13.5
	Huang et al. ⁴³	food production		9.2				
	Gu et al. ⁴⁴	food production					12.3	
	Crippa et al. ⁴⁵	food production	9.5				12.5	
	Dianwu and Anpu ⁴⁶	food production (76%) + other	13.6					
	Streets et al. ⁴⁷	food production (80%) + other (20%)	13.6					
	Gu et al. ⁴⁸	food production (88%) + other				11.2		
	Ti et al. ⁴⁹	food production + other	10		9.8			
	Cui et al. ⁵⁰	food production + other					10	
	Kurokawa et al. ⁵¹	food production (80%) + other (20%)	12.5	14.3		14.8		
N ₂ O	This study	food production	0.4					0.4
	Zhou et al. ⁵²	food production				1.4 ^a		
	Gu et al. ⁴⁴	food production					0.4	
	Crippa et al. ⁴⁵	food production	0.6					0.9
	Gu et al. ⁴⁸	food production (45%) + other				1.1		
	Cui et al. ⁵⁰	food production + other					0.4	
Total N to waters	This study	food production	9.2					12.8
	Gu et al. ⁴⁴	food production					7.8	
	Strokal et al. ³²	food production (six river basins)	8.5					
	Ti et al. ⁴⁹	food production + other	8.8		9.3			
	Cui et al. ⁵⁰	food production + other					12	
Total P to waters	This study	food production	1.5					2.5
	Strokal et al. ³²	food production	1.3					
	Liu et al. ⁵³	food production + other						1.7

^aThis study accounts for nitrous oxide (N₂O) emissions from the burning of straw (0.5), which we do not consider. However, our results shows similar spatial patterns to those in this study.

much higher than in other counties in 2012 (Figures 3 and 4, $P < 0.05$). For example, the mean synthetic fertilizer input in the hotspots was 400% higher for N, and 300% higher for P than that in other counties (Table S7). Mean animal numbers in the hotspots were five times that in other counties in 2012 (Table S7).

The N and P use efficiencies of food production are calculated to be low and their means are comparable between hotspots and nonhotspot counties (Figures 3 and 4, Figures S4 and S5, $P > 0.05$). The average nutrient use efficiency of food production in Chinese counties was 24% for N, and 29% for P in 2012 (Table S7). This is lower than the nutrient use efficiency in 1990 that was 25% for N and 38% for P (Figures S4 and S5). Howarth et al.³⁸ estimated the N use efficiency of main crop production at 56% in United States in 2000. And in Europe the N use efficiency of main crop production was around 44% in 2000.³⁹ This indicates that in general the nutrient inputs in food production in China are not used efficiently because of poor nutrient management in food production, and as a consequence losses of nutrients to the air and waters are relatively high. However, the fact that nutrient use efficiencies in hotspots do not differ from those in nonhotspots, indicates that low N and P use efficiencies are not the only reason for the high losses in the hotspots. The high N and P losses are the net effect of low N and P use efficiencies, intensive food production (e.g., large animal numbers), and poor nutrient management technologies (e.g., overuse of synthetic fertilizer, and high direct discharge of manure to waters as mentioned above) in the hotspots.

The shares of vegetables and fruits in the total sown area in the hotspots are comparable to that in nonhotspot counties (Figures 3 and 4, Figures S4 and S5, $P > 0.05$). Production of

vegetables and fruit was not found to be more intensive in hotspots than in other counties. This is surprising since earlier studies indicate that nutrient losses from fruit and vegetable production are usually higher than that in other cropping systems as a result of high synthetic fertilizer application.^{40–42}

Socio-economic indicators also differ between hotspots and other counties (Figures 3 and 4, Figures S4 and S5, $P < 0.05$). Hotspots are less urbanized. On average less than 20% of population was urban in the hotspots in 2012 (Table S7). On the other hand, the mean number of people working in food production in hotspots was three times that in nonhotspot counties in 2012 (Table S7). The mean incomes for farmers who work in food production were over 30% higher in the hotspots than that in the nonhotspot counties (Table S7). Also the mean total output value from agriculture and forestry in these hotspots was considerably higher (close to five times) than in other counties in 2012 (Figures 3 and 4, $P < 0.05$). Therefore, farmers' incomes in the hotspots seem to be more dependent on food production.

DISCUSSION

This study is the first to calculate past (1990 and 2000) and more recent (2012) N and P losses to the environment from food production in China at the county scale. On this basis we identified the associated hotspots for N and P losses from food production. We compared several agricultural and socio-economic indicators for the hotspots with that for other counties in 2012. The main findings are as follows.

We calculate a larger hotspot area for 2012 than for 1990, indicating N and P losses from food production increased in this period. In 2012, the hotspots covered 9% of the total land, but were responsible for 52% of total N losses and 62% of total

P losses in China. Nutrient losses from food production in the hotspots are higher than 9625 kg km^{-1} for N, and 905 kg km^{-1} for P. Note that these losses are even higher than the recommended fertilizer inputs to arable land. For example, the United Kingdom suggests to apply $120\text{--}270 \text{ kg ha}^{-1}$ N on arable land.⁵⁴ Such high losses to the air and waters pose potentially high risks to the environment. The direct discharge of animal manure has become an important source of N and P losses in food production over the last 30 years as the result of industrialization of animal production in China as indicated in Table S9.

The hotspots expanded from part of North China in 1990 to most of the area of North China Plain, and some areas of other eastern AEZs in 2012. Food production in the hotspots are found to be intensive. Mean synthetic fertilizer use and mean animal numbers in hotspots were 300–400% higher than that in nonhotspot counties in 2012. N and P use efficiencies of food production were generally low (24% for NUE, and 29% for PUE) in 2012 and did not differ much between hotspots and nonhotspot counties. Therefore, low use efficiency of nutrients is not the only factor to explain the high losses of N and P in hotspots. The high losses of N and P in the hotspots are the net effect of the low N and P use efficiencies, and the intensive food production in these counties. Less than 20% of the population is urban in hotspots in 2012. The mean number of people working in food production in hotspots was three times that in other counties in 2012. The mean total output value from agriculture and forestry in hotspots was considerably higher than that in other counties in 2012. Therefore, farmers' incomes in hotspots seem to be more dependent on food production than other counties.

Uncertainties in our analysis are mainly related to the model inputs and the coefficients that are used in the model calculation. In this study, we used county data from the Chinese statistical year book as inputs to *NUFER*. Some of the model inputs were missing in this data set. For the incomplete information, the provincial data from Chinese statistical year book and China livestock yearbook were used as complement (see section S2 in the Supporting Information for more details). These statistical yearbooks are known to be the most reliable data source in China. The model coefficients (e.g., nutrient content in crops, nutrient loss factors) are from the original *NUFER* model, which was taken from other peer reviewed papers and interviews of farmers in China.²⁸ Our results are comparable with other studies. For example, we estimated comparable NH_3 losses from food production to the air, and N and P losses to waters at the national scale with many of the other studies (Table 1). Our estimates of N_2O emission in 2012 is lower than in the other studies (Table 1). A likely explanation is that N_2O emission from the burning of straw was not considered in our study. This can be improved in our model. However, we do not think this will lead to large change in our conclusions since N_2O losses are minor compared to other losses of reactive N from food production (Figures 1 and 2). Huang et al.,⁵⁵ Kang et al.,⁵⁶ Zhang et al.⁵⁷ calculated similar spatial distribution patterns for NH_3 emissions as we did. The study of Gu et al.⁴⁸ identified similar spatial distribution of NH_3 and N_2O emissions from food production and other human activities and calculated a considerable increase in these emissions between 1990 and 2010. Similar spatial distribution of P losses from food production and other sectors in 2012 was also identified by Liu et al.⁵³

Opportunities to Reduce N and P Losses. Our results show that hotspots contributed to more than half of total N and total P losses from food production in China, while covering less than 10% of the country area in 2012. Thus, it is important to reduce the nutrient losses from food production in these hotspots in order to control nutrient pollution in China. Region-specific nutrient management needs to be developed for the hotspots particularly for the North China Plain where N and P losses are relatively high, and the food production activities are more intensive than other regions. By comparing the socio-economic indicators in hotspots and nonhotspots, we found that farmers' incomes in hotspots are more dependent on food production. Therefore, the production of food in the hotspots needs a transformation in order to avoid negative effects of pollution on the economies of local societies.

There are many technical improvements possible to reduce losses of nutrients. In crop production, techniques that help to fertilize crops based on their specific needs could reduce N and P inputs to land by up to 20%, and improve the associate nutrient use efficiencies in the hotspots.^{13,58–60} Increasing farm sizes may also decrease the use of synthetic fertilizer in crop production.⁶¹ Nutrient losses to the air and waters could be reduced by up to 60% for N, and 85% for P without reducing crop yields, needed to meet the increasing food demand in China.⁶⁰ This also secures the interests of farmers since their incomes are dependent on food production. Low-emission technologies (e.g., inject animal manure into soil) could be adopted to reduce the NH_3 and N_2O emission from applying fertilizers on cropland.^{26,62,63} Experimental and modeling studies^{58,59,64,65} that explore and implement the above-mentioned techniques in the North China Plain could be used as a good basis for the nutrient management in hotspots. The intensive industrial animal production leads to large N and P losses to the environment in the hotspots. Technologies that improve the quality of animal feed could reduce 20–30% of the N and P excretion,^{39,66,67} thus reduce the overall N and P losses from animal production. The N and P losses to waters from direct discharge of manure could be much reduced by up to 85% via recycling animal manure on cropland as organic fertilizers and by improving the treatment of animal manure before discharging.^{60,68} The N and P losses to the air from animal production can be reduced in several ways, for instance by shifting to low emission housing and manure storage technologies that are currently used in some European Union (EU) countries.⁶⁹ The above nutrient management options are technically effective in reducing N and P losses. In future analyses, it is important to also explore whether these options are economically affordable, because implementation of these options may be a challenge in China.

In summary, our study can be used to identify hotspot counties where pollution control technologies are needed to reduce N and P losses from food production. This holds in particular for technologies to reduce synthetic fertilizer use, to improve nutrient use efficiencies of food production, to reduce emission of N in animal housing and manure storage, and to increase recycling of manure on land. The challenge will be to secure food production so that farmers' interests are not negatively affected by pollution control.

■ ASSOCIATED CONTENT

📄 Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: [10.1021/acs.est.7b06138](https://doi.org/10.1021/acs.est.7b06138).

This file includes detailed calculation methods, tables, and figures of additional data (Figures S1 to S9, Tables S1 to S9, Boxes S1 to S3, and References) (PDF)

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Notes

The authors declare no competing financial interest.

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