Journal of Environmental Management 263 (2020) 110400

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: http://www.elsevier.com/locate/jenvman

Research article

Assessment and analysis of agricultural non-point source pollution loads in China: 1978–2017

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ARTICLE INFO

Keywords:
Non-point source pollution
Inventory analysis
Chemical oxygen demand
Total nitrogen
Total phosphorus

ABSTRACT

China's successful agriculture development has resulted in public concerned environmental problems. However, continuous and detailed data about Chinese agricultural non-point source pollution (ANPSP) loads are lacking. To assess and analyze Chinese ANPSP loads from 1978 to 2017, an inventory analysis was performed, and a socioeconomic and spatiotemporal analysis in the scale of provinces was conducted. The results showed that the pollution loads of chemical oxygen demand (COD), total nitrogen (TN) and total phosphorus (TP) increased by 91.0%, 196.2% and 244.1%, respectively, and their variation underwent a free development stage, reform promotion stage, market regulation stage and policy incentive stage. The results of the pollution source analysis showed that over the past 40 years, the total percent contribution to COD by livestock and poultry breeding (LPB) and rural household waste (RHW) accounted for 83.1%–96.6%, the total percent contribution to TN by mineral fertilizers (MF) and LPB accounted for 72.3%–80.8%, and the total percent contribution to TP by LPB, RHW and MF accounted for 69.1%–88.6%. In addition, Shandong, Guangdong, Sichuan, and Henan were the top producers of ANPSP loads, and their COD, TN, and TP loads accounted for approximately 32%, 30%, and 35% of the national totals, respectively. The discharge intensity of COD, TN and TP decreased by 79.2%, 67.8%, and 62.6%, respectively. The discharge intensity exhibited a phasic feature that aligned with the national economic plan in the temporal scale and was closely related to the agricultural conditions in the spatial scale.

1. Introduction

Since the reform and opening-up,[1] China's grain yield has increased from 304.77 million tons in 1978 to 617.91 million tons in 2017, and meat output has increased from 8.56 million tons to 86.54 million tons (Ministry of Agriculture of the People's Republic of China, 2010; Rural Social Economic Investigation DivisionNational Bureau of Statistics, 2018). Simultaneously, the application of mineral fertilizers increased from 8.84 million tons in 1978 to 58.59 million tons in 2017, and the application of plastic film and pesticides increased from 0.48 million tons and 0.73 million tons in 1990 to 2.53 million tons and 1.66 million tons in 2017, respectively (Rural Social Economic Investigation DivisionNational Bureau of Statistics, 2018). The utilization rate of fertilizers and pesticides was less than 1/3, the recovery rate of plastic film was less than 2/3, the effective treatment rate of livestock waste was less than 50%, and straw incineration and water eutrophication were serious (Ministry of Agriculture et al., 2015). Thus, it could be observed that agricultural growth depended on the intensive input of production factors, and this type of agricultural pattern characterized by a high yield, low efficiency and high input (Rao et al., 2012; Zhang et al., 2019a) has caused serious non-point source (NPS) pollution problems in water environments, among which agricultural pollution poses the greatest threat (Fan et al., 2019).

Agricultural non-point source pollution (ANPSP) caused by intensive agrochemical input in agricultural production activities greatly contributes to declining water quality and aquatic ecosystems (Bryan and Kandulu, 2011; Zhang et al., 2019a). ANSP is characterized by varying spatial and temporal pollutant loading, and complex processes and

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[1] The reform and opening-up policy of China was based on the theory proposed by Deng Xiaoping and enacted by the Third Plenum of the 11th Party Congress of the People Republic of China in 1978. This policy was characterized by distributing rural land to households and establishing a socialist market economic system.

https://doi.org/10.1016/j.jenvman.2020.110400
Received 7 August 2019; Received in revised form 21 February 2020; Accepted 3 March 2020
Available online 12 March 2020

mechanisms with arbitrary and irregular occurrence (Jin et al., 2019). Complexities in monitoring and controlling makes ANSP more complicated than point source pollution (Adu and Kumarasamy, 2018). Studies have confirmed that ANPSP has become a focus in the field of water pollution control worldwide. For example, the Environment Protection Agency in the USA reported that five of the top six identified sources of river and stream quality impairments were NPS (Brown and Froemke, 2012), and approximately 67% of lakes, reservoirs, and ponds and 53% of rivers and streams were classified as impaired in 2013 (Niraula et al., 2013). In the European Union and Germany, agriculture contributes to NPS pollution in surface waters, accounting for approximately 55% and 48%, respectively (Volk et al., 2009). In China, the Bulletin of the First National Pollution Source Census showed that in 2007, China's discharges of agricultural chemical oxygen demand (COD), total nitrogen (TN) and total phosphorus (TP) accounted for 43.7%, 57.2% and 67.4% of all pollutant discharges, respectively. Therefore, it is important to accurately estimate the ANPSP loads to address the critical agricultural pollution situation.

Many methods have been used to estimate agricultural pollution loads, and the original method was developed in North America in 1960s. In the early 1980s, this method was introduced to China in a study investigating urban runoff pollution (Ongley et al., 2010). Generally, the models adopted are divided into empirical models, such as ECM (Han et al., 2011; Ma et al., 2011), IECM (Cheng et al., 2018; Wu et al., 2015) and HSM (Zhang et al., 2019a), and mechanism models, such as SWAT (Chen et al., 2019; Zhang et al., 2019b), AGNPS (Haregeweyn and Yohannes, 2003; Liu et al., 2008) and HSPF (Nayeb Yazdi et al., 2019; Ribarova et al., 2008). Most models have good performance based on the method and simulation results, but both advantages and disadvantages are apparent in the data-sensitivity and regionality (Adu and Kumarasamy, 2018; Ongley et al., 2010; Shen et al., 2012). On the one hand, the estimation accuracy of almost all models depends on a large number of parameters, requirements for a large body of input data, and unlimited available information, leading to difficulties in calibrating and validating these models (Guo et al., 2014; Xin et al., 2017). On the other hand, although most methods show a good estimation effect in developed countries, representing where the methods are designed, they may not be suitable for developing countries considering the differences between the actual environmental conditions and the experimental conditions (de Oliveira et al., 2017; Wu et al., 2015).

China is the largest developing country with heavy agriculture and is facing a very serious problem due to agricultural pollution (Deng and Gibson, 2019). Although some data regarding agricultural pollution can be acquired from published studies and official statistics, more information regarding the pollution loads over a long period is rarely accessible because of the lack of technical verification and statistical systems (Adu and Kumarasamy, 2018). In addition, the agricultural pollution sources involved in the bulletin were limited to the crop industry, breeding industry and rural life (Chen et al., 2006; Zhang et al., 2018). This report narrowed the source scope, leading to inconsistent measures of agricultural pollution loads. Moreover, most studies performing ANPSP load estimation concentrated on a certain watershed (Cheng et al., 2019; Shen et al., 2014; Zhang et al., 2019b) or a certain geography unit (Wang et al., 2016, 2019) rather than the whole country and focused on the technological aspect (Shen et al., 2014; Xin et al., 2017; Zhang et al., 2019a), but the socioeconomic aspect is poorly understood (Fan et al., 2019; Lu and Xie, 2018). Therefore, our aim is to estimate a long time series of ANPSP loads in China within the whole country, incorporate more agricultural pollution sources, and analyze the spatial and temporal variation.

To estimate the ANPSP loads in China, an inventory analysis, which was developed to estimate pollution loads by using input production factors that are relatively easy to obtain from statistics, is used (Chen et al., 2006). This approach greatly decreases the consideration of complex pollution processes and mechanisms and largely reduces the cost of experimental monitoring and modeling (Lai, 2004); this analysis provides a certain level of accuracy in the estimation of pollution loads, especially in large-scale administrative regions (Paepe et al., 2002). Based on this analysis, the objectives of this study are to estimate the provincial ANPSP loads in China from 1978 to 2017; (2) distinguish the main sources of agricultural pollution; (3) analyze the changes of discharge intensity and regulation mechanisms of national agricultural policies. The remainder of this paper is organized as follows: Section 2 describes the research materials and methods used in the study, Section 3 presents and discusses the empirical results, and Section 4 concludes the study.

2. Materials and methods

2.1. Research materials

To estimate the ANPSP loads in China, an agricultural input and output database is established; the database includes provincial annual data of the total grain yield and meat output; the pure consumption of nitrogen, phosphate and compound fertilizers; the numbers of slaughtered swine and poultry; the year-end total numbers of cattle and sheep; the aquatic production in freshwater and marine; the yield of rice, wheat, corn, vegetables, beans, tubers and oil-bearing crops; and the rural population from 1978 to 2017. In addition, the provincial annual gross values of agriculture, forestry, animal husbandry and fishery (AFAF) are included.

Most data are derived from the *China Rural Statistical Yearbook (Sta1), Agricultural Statistical Compilation for 30 years of Reform and Opening-up (Sta2), Agricultural Statistics for 50 years in New China (Sta3), Agricultural Statistics for 60 years in New China (Sta4), China Statistical Yearbook (Sta5), China Fishery Statistical Yearbook (Sta6), China Marine Statistical Yearbook (Sta7), China Agricultural Machinery Industry Yearbook (Sta8), Chinese Agricultural Statistical Compilation (Sta9),* and *China Population & Employment Statistics Yearbook (Sta10)*. The AFAF values are derived mainly from the *China Rural Statistical Yearbook* (1986–2018) and provincial statistical yearbooks (1979–1985). Because the AFAF value was obtained according to the current year's price, inflation is corrected by the annual value index of AFAF based on 1978. The study area includes 31 provinces, excluding Hong Kong, Taiwan, and Macao. Due to administrative adjustments, data from Chongqing during the 1978–1996 period were included for Sichuan Province, and data from Hainan Province during the 1978–1987 period were included for Guangdong Province.

Fig. 1 shows that the major grain provinces mainly concentrated in the northeast and central China; the major meat provinces mainly concentrated in north, central and south China; and the major aquatic provinces mainly concentrated in the southeast coast and central China. Except for the aquatic product output, the geographical pattern of the production factor input was basically the same as that of the agricultural output. The agricultural input and output of Shandong ranked among the top three, and Henan was the same, except for the aquatic product output.

2.2. Research methods

Inventory analysis is an inexpensive and manageable method suitable for long-term and average rural pollution estimating (Chen et al., 2006). The core of inventory analyses is to identify the elementary unit (EU) of agricultural pollution sources, which is the minimum independent unit that can be reasonably measured. Generally, in China, the agricultural pollution sources mainly include three categories. First, NPS pollution in farmland production originates from the application of mineral fertilizers, plastic film and pesticides, straw burning and stacking, etc. Second, NPS pollution originates from breeding, such as livestock and poultry breeding, aquaculture, etc. Third, NPS pollution originates in rural living, such as rural residents' excrement and urine, residential sewage and garbage, etc. More concretely, the pollution

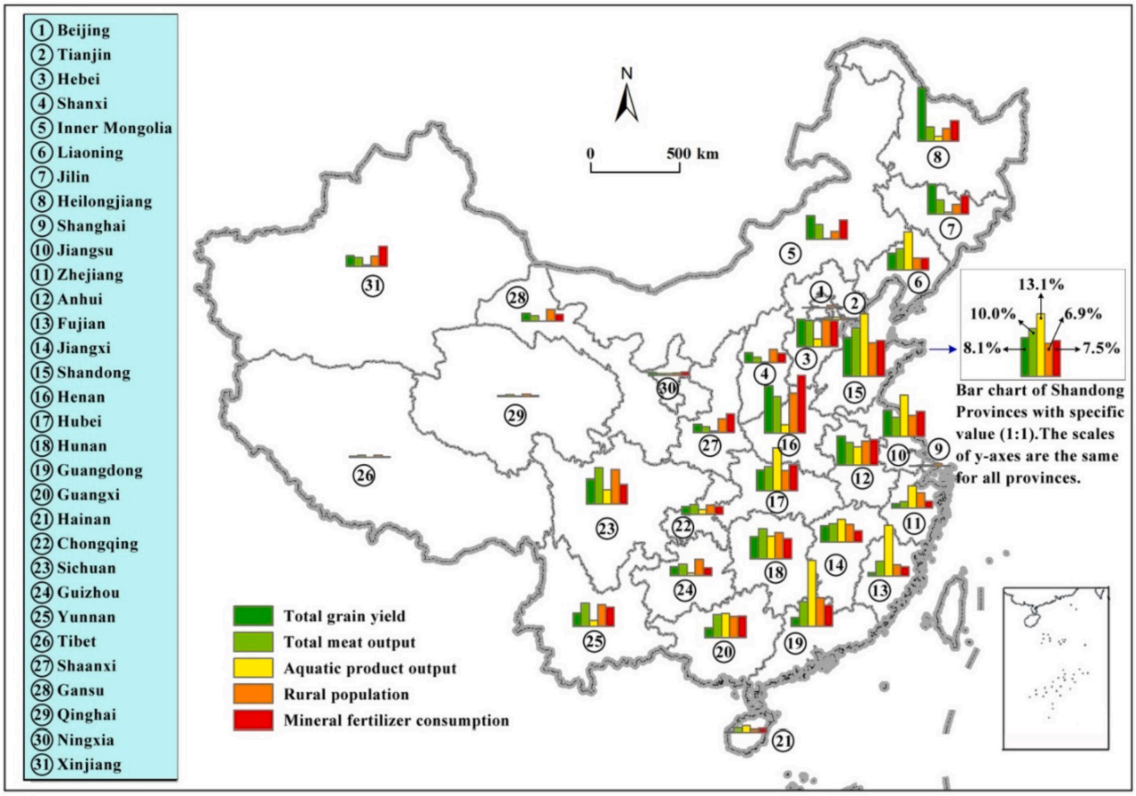


Fig. 1. Geographical pattern of the proportion of partial agricultural input and output in China's provinces in 2017. The length of the color bars on the y-axis represents the proportion of input and output per province to the whole country.

sources estimated in this study include mineral fertilizers, livestock and poultry breeding, aquaculture, farmland straw, and rural household waste. Notably, plastic film and pesticide pollution are not considered in this paper due to the lack of referable pollutant parameters. To measure and compare various pollutants on a uniform scale, the pollutants are calculated as COD, TN and TP, which are the main components of ANPSP.

According to Lai (2004) and Chen et al. (2006), an EU list of a four-tier structure composed of activity, class, unit, and indicator is presented in Table 1. By employing a 'top-down' approach, the links between activities and total pollution loads (TPL) can be derived using the following formula (1):

$$TPL = \sum EU_{activity} = \sum\sum EU_{class} = \sum\sum\sum EU_{unit} * EUA \tag{1}$$

where TPL represents the TPL of ANPSP (10^4t); $EU_{activity}$ represents the pollution loads of agricultural activities (10^4t); EU_{class} represents the pollution loads of agricultural classes (10^4t); EU_{unit} represents the pollution loads of agricultural units (10^4t); and EUA represents the discharge amount of EU, which is calculated by the following formula (2):

$$EUA = \sum_i EU_i \rho_i (1-\eta_i) C_i(EU_i, S) = \sum_i PE_i \rho_i (1-\eta_i) C_i(EU_i, S) \tag{2}$$

where EU_i represents the indicator statistics in unit i; ρ_i represents the pollutant-production coefficient in unit i; η_i represents the coefficient that characterizes the utilization efficiency of the relevant resource; PE_i represents ANPSPs' production amount (10^4t), i.e., the maximum potential pollutants caused by agricultural production without considering the comprehensive utilization of resources and management factors; and C_i represents the pollutant-discharge coefficient in unit i and is determined by S, which is characterized by the combined effect of the regional environment, rainfall, soil, vegetation and various management measures applied to agricultural pollution. This study used the experimental parameters described by Lai (2004) and the correlation coefficients from the *First National Pollution Source Census* as the pollutant-production and pollutant-discharge coefficients.

The *TPL* can only reflect the regional pollution loads and cannot reveal the social cost of agricultural pollution. Therefore, an in-depth analysis of the discharge intensity can more objectively reflect the social risk of agricultural pollution. The pollution sources investigated in this study include not only mineral fertilizers and farmland straw but also livestock and poultry breeding, aquaculture and rural household waste. Therefore, the discharge intensity of ANPSP is measured by the amount of pollutant discharges per-unit value of AFAF, which is calculated as follows:

$$DI = \frac{TPL}{OL} \times 10^{-4} \tag{3}$$

where DI is the discharge intensity of ANPSP (t/¥10^4yuan), which is a practical indication of the severity of agricultural pollution and characterizes the social cost of ANPSP; OL is the value of AFAF (¥10^4yuan).

3. Results and discussion

3.1. Model calibration and validation

The total pollution loads of COD, TN and TP are calculated by formulas (1) and (2). Because detailed pollution data are scarce, the results' rationality could only be validated by comparing with the data reported by Lai as shown in Table 2. It is found that the COD, TN and TP productions and discharges are basically consistent, except for the pollutant discharges of livestock and poultry breeding. As shown in Table 2, the pollutant productions of livestock and poultry breeding in this study and those reported by Lai are the same; thus, we infer that there may be some computational errors in Lai's study. To prove this hypothesis, the

Table 1
List of the elementary unit and data sources of agricultural non-point source pollution in China.

Activities	Classes	Units	Indicators	Data sources
Mineral fertilizers	Nitrogen fertilizer (NF)	NF use for grain crops NF use for vegetables NF use for other crops	Pure consumption (10^4t)	The data from 1985 to 2017 are obtained from the *Sta1*; the data from 1978 to 1984 are calculated by the trend extrapolation approach based on the total amount of *Sta2*
	Phosphate fertilizer (PF)	PF use for grain crops PF use for vegetables PF use for other crops	Pure consumption (10^4t)	
	Compound fertilizer (CF)	CF use for grain crops CF use for vegetables CF use for other crops	Pure consumption (10^4t)	
Livestock and poultry breeding	Livestock	Cattle	Year-end total number (10^4head)	The numbers of cattle, sheep and swine in 1985–2017 are obtained from the *Sta1*, and those in 1978–1984 are obtained from the *Sta2*; the numbers of poultry in 1992–2017 are obtained from the *Sta1*, and those in 1978–1991 are obtained from the *Sta2*
		Sheep	Year-end total number (10^4head)	
		Swine	Numbers slaughtered (10^4head)	
	Poultry	Poultry	Numbers slaughtered (10^4head)	
Aquaculture	Freshwater aquaculture	Fish	Fish output (10^4t)	The data are mainly obtained from the *Sta1*, except for a few years, for which the data are obtained from the *Sta5, Sta6, Sta7,* and *Sta8*
	Mariculture	Fish	Fish output (10^4t)	
		Crustaceans	Crustacean output (10^4t)	
		Shellfish	Shellfish output (10^4t)	
Farmland straw	Grain crops	Rice Wheat Corn Beans Tubers	Yield (10^4t) Yield (10^4t) Yield (10^4t) Yield (10^4t) Yield (10^4t)	The data from 1985 to 2017 are obtained from the *Sta1;* the data from 1978 to 1984 are obtained from the *Sta2;* the vegetable output of a few years is calculated based on the planting area
	Economic crops	Oil-bearing crops	Yield (10^4t)	
	Horticulture crops	Vegetables/fruits	Yield (10^4t)	
Rural household waste	Domestic sewage	Person	Rural population (person)	The data from 2006 to 2017 are obtained from the *Sta10;* the data from 1978 to 2005 are obtained from the *Sta2*
	Living manure	Person	Rural population (person)	

pollutant discharges of livestock and poultry breeding are recalculated in Appendix 1 by using this study's pollutant productions and Lai's pollutant-discharge coefficient. The recalculation shows that the discharges in this study are reasonable and could be used to reflect Chinese ANPSP loads over the past 40 years.

3.2. Total agricultural non-point source pollution loads

The pollution loads of all pollutants are generally increasing as shown in Fig. 2. The total pollution loads increased from 1955.1 × 10^4 tons in 1978–4179.3 × 10^4 tons in 2017. Concretely, the pollution loads of COD increased from 1553.3 × 10^4 tons in 1978–2967.6 × 10^4 tons in 2017; the pollution loads of TN increased from 356.6 × 10^4 tons in 1978 to 1056.4 × 10^4 tons in 2017; and the pollution loads of TP increased from 45.1 × 10^4 tons in 1978 to 155.4 × 10^4 tons in 2017. The pollution loads of these pollutants increased by 91.0%, 196.2%, and 244.1%, respectively.

Overall, the total pollution loads underwent four stages from 1978 to 2017 as shown in Fig. 2. From 1978 to 1985, the pollutant loads experienced the first stage of free development. Due to the lack of a market mechanism and national policy, the pollutant loads slightly increased. From 1986 to 1996, the pollutant loads experienced the second stage of reform, which was characterized by promoted growth, and the pollutant loads greatly increased by the marketized reform of agricultural products. The first reduction in pollutant loads occurred in 1997, which was rooted in the fact that the Asian Financial Crisis led to a significant reduction in the number of livestock and poultry breeding. Compared with 1996, the numbers of slaughtered swine and poultry were reduced by 11.7% and 11.1%, and the year-end total numbers of cattle and sheep were reduced by 12.9% and 15.7%, respectively. Subsequently, the pollution loads experienced the third stage of market regulation growth during the 1997–2006 period. Under the self-regulation market mechanism, the pollutant loads slowly increased and reached the highest value in 2005. The second reduction in pollution loads occurred in 2007 as the World Financial Crisis led to a sharp reduction in the number of livestock and poultry breeding. Compared with 2006, the number of slaughtered swine decreased by 17.0%, and the year-end total numbers of cattle and sheep decreased by 24.0% and 22.6%, respectively. Subsequently, during the 2007–2017 period, the pollution loads experienced the fourth stage, which was characterized by a policy of incentive growth, and the introduction of a series of favorable agricultural policies led to a slow increase in the pollutant loads.

Over the last 40 years, China's grain yield and meat products experienced several bouts of growth, and the pollution loads soared and appeared to undergo a staged change. During the process, the change in the agricultural production structure was an external driving force leading to an increase in the pollutant loads, while the change in the food consumption structure was an internal driving force, and both changes are due to the rising income level caused by the development of the nonagricultural economy (Huang, 2016). The impact of the transformation of the domestic economic system and the sudden change in the international economic situation on the agricultural product market were important node events leading to the change in the pollution loads (Fan et al., 2019). First, in 1985, the state gradually liberalized the control of the major agricultural products market and began to introduce the market mechanism to the development of agriculture and the rural economy, which fully stimulated the commodity attributes of agricultural products. Under the encouragement of the policy to return farmland to families, food production continued to increase, thereby resulting in a continuous increase in the pollutant loads. Second, the impact of the 1997 Asian Financial Crisis and the 2007 World Financial Crisis on livestock and poultry breeding directly led to a shift in the pollutant loads, which synchronized its changes to the economic cycle (Zhang et al., 2016). The changing trend of the pollution loads indicates that China's agriculture still relies on the input of production factors to reach an output growth stage (Wang and Liu, 2018), which is the direct

Table 2
Comparisons of the results of this study (TS) and Lai's study (Lai) in 2002.

Pollutant sources	Pollutant productions (TS)			Pollutant productions (Lai)			Pollutant discharges (TS)			Pollutant discharges (Lai)		
	COD	TN	TP	COD	TN	TP	COD	TN	TP	COD	TN	TP
Mineral fertilizers		2501.13	469.56		2504.60	462.49		449.33	24.96		449.94	24.59
Livestock and poultry breeding	9077.24	1356.35	338.16	9081.40	1356.35	338.16	**2143.63**	**269.08**	**55.12**	**2219.52**	**282.77**	**46.79**
Farmland straw	669.13	514.55	84.58	664.47	513.56	84.00	175.27	63.39	16.93	170.23	62.52	16.15
Rural household waste	2397.41	340.72	62.65	2397.41	340.72	62.65	731.19	83.22	18.70	731.19	83.22	18.70
Total	12143.78	4712.75	954.95	12143.28	4715.23	947.3	3050.09	865.02	115.71	3120.94	878.45	106.23

Note: COD, TN and TP are abbreviations of chemical oxygen demand, total nitrogen and total phosphorus, respectively. The value of the number is 10^4t.

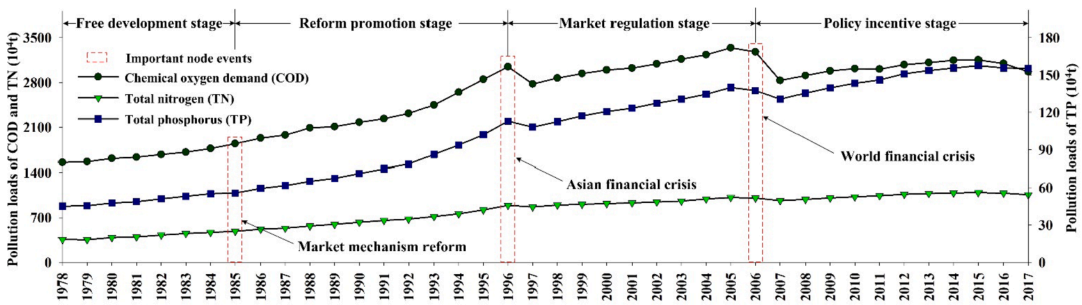


Fig. 2. Total pollution loads of agricultural NPS pollutants between 1978 and 2017 in China. The y-axis on the left represents the pollution loads of COD and TN, and the right y-axis represents the pollution loads of TP.

cause leading agricultural pollution to exceed industrial pollution as the main source of water pollution.

3.3. Contribution of agricultural non-point source pollution loads

3.3.1. Contribution of different pollutant sources

Livestock and poultry breeding and rural household waste were the main sources of COD, and their total percent contribution decreased from 96.6% to 83.1% during the 1978–2017 period. Since the numbers of slaughtered swine and poultry increased by 3.3 times and 24.0 times and the year-end total number of cattle and sheep increased by 0.5 times and 0.8 times, the percent contribution to COD by livestock and poultry breeding increased from 56.8% to 68.1%. Furthermore, the percent contribution to COD by rural household waste decreased from 39.8% to 15.0% because the rural population switched from increasing to decreasing in 1996 (Fig. 3a).

The main sources of TN were mineral fertilizers and livestock and poultry breeding, and their total percent contribution decreased from 73.0% to 72.3% during the 1978–2017 period; the highest value was 80.8%. As pure fertilizers' consumption increased by 3.7 times, it's percent contribution to TN increased from 42.2% to 48.2%. Although the number of livestock and poultry breeding increased by multiple times, it's percent contribution to TN decreased from 30.9% to 24.0% because the growth rate of nitrogen discharge from mineral fertilizers is 1.5 times of that from livestock and poultry breeding (Fig. 3b).

The main sources of TP were decentralized and changeable. Before 1993, the main sources were livestock and poultry breeding and rural household waste, and their total percent contribution decreased from 74.9% to 65.8% during the 1978–1992 period. Subsequently, the main sources were livestock and poultry breeding and mineral fertilizers, and their total percent contribution decreased from 64.9% to 61.8% during the 1994–2017 period. The total percent contribution of the three types of pollution sources decreased from 88.4% to 69.1% during the 1978–2017 period, and the highest value was 88.7%. Concretely, the percent contribution to TP by livestock and poultry breeding slightly decreased from 39.9% to 39.0%, while the percent contribution of rural household waste decreased from 35.0% to 7.3%, and the percent contribution of mineral fertilizers increased from 13.5% to 22.8% (Fig. 3c).

In addition to the main sources, the percent contributions of other pollution sources also deserve attention. For example, the percent contribution by farmland straw did not dominate with an increase in grain output (the output of rice, wheat, corn, vegetables, beans and oil increased by 3.7 times), but China performed crop residue burning for a long time and has suffered from resultant environmental pollution (Yu et al., 2019); although the percent contribution of aquaculture was low, the worsening eutrophication and the resulting 'red tide' (Cai et al., 2013; Meng and Feagin, 2019) have become increasingly serious as the output of aquatic products continued to rise (the output of aquatic products increased by more than 40 times). Furthermore, mineral

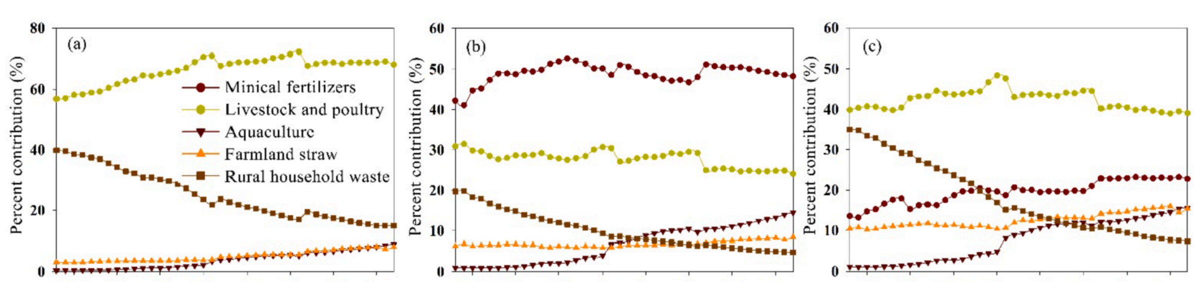


Fig. 3. Percent contributions to chemical oxygen demand (a), total nitrogen (b) and total phosphorus (c) by different pollution sources from 1978 to 2017 in China. The y-axis represents the percent contribution to a pollutant from a source to the total amount of that pollutant.

fertilizers had the highest contribution to TN, indicating that the ongoing nitrogen reduction policy based on changing the agricultural fertilization structure was effective (Wu and Ge, 2019); however, livestock and poultry breeding had the greatest contribution to COD and TP, indicating that the current pollution control policy should also target livestock and poultry breeding (Yang et al., 2013), especially in the policy context of stabilizing swine production.

3.3.2. Contribution on a provincial scale

Since the socioeconomic structure, agricultural practices, and rural conditions are difficult to change in a short time (Shen et al., 2014; Yu et al., 2019), the average percent contribution within two consecutive Five-Year Plans (FYPs),[2] which is basically consistent with the four stages of pollution loads, are selected to reveal the differences in the provincial contribution. Obviously, the percent contributions to the agricultural pollutants significant differ across the provinces. As shown in Fig. 4, Shandong, Guangdong, Sichuan, and Henan were the top producers of ANPSP loads. Their COD, TN, and TP loads accounted for approximately 32%, 30%, and 35% of the national totals, respectively. The results are consistent with the fact that the four provinces were major agricultural areas with large rural populations (Chen et al., 2006). In addition, Jiangsu, Hebei, Hunan, and Hubei are the secondary producers of ANPSP loads, and their COD, TN, and TP loads accounted for approximately 18%, 25%, and 20% of the national totals, respectively. Although the agricultural areas in these four provinces are relatively small, some practices of intensive agricultural measures, such as multiple cropping, intercropping, large scales of livestock production, and overapplication of mineral fertilizers, has caused high pollution loads.

Obviously, the basic agricultural conditions and agricultural production structure are the main factors determining the differences in the provincial percent contributions to agricultural pollutants (Zhang et al., 2011). It has been indicated that although China's agricultural reform has experienced historical progress in modernization marked by an increase in labor productivity and farmers' income (Wang et al., 2019), such progress differs from that in developed countries, such as European countries and the United States, or the so-called "East Asian model" (Huang, 2016). The "hidden agricultural revolution" is caused by an interaction among the human-land relationship, resource endowment and state behavior. In addition, notably, the percent contributions to agricultural pollutants in Beijing and its surrounding six provinces were quite different. The percent contribution in Beijing and Shanxi had declined yearly, while that in Inner Mongolia and Henan had increased. There was a significant decline in Tianjin, Hebei and Shandong since 2006 because China had developed a series of pollution reduction programs for the provinces surrounding Beijing to meet the 2008 Beijing Olympic Games. This finding indicated that the effect of synergistic pollution reduction in the surrounding provinces of Beijing was characterized by "tightness inside and looseness outside".

3.4. Discharge intensity of agricultural non-point source pollution

The discharge intensity of pollutants can be calculated by formula (3). As shown in Fig. 5, the discharge intensity of COD decreased from 11119 tons/¥10^4 yuan in 1978–2309 tons/¥10^4 yuan in 2017; the discharge intensity of TN decreased from 2553 tons/¥10^4 yuan in 1978 to 822 tons/¥10^4 yuan in 2017; and the discharge intensity of TP decreased from 323 tons/¥10^4 yuan in 1978 to 121 tons/¥10^4 yuan in 2017. The discharge intensity of these pollutants decreased by 79.2%, 67.8%, and 62.6%, respectively. More concretely, during the period of the 5th FYP and 6th FYP (1978–1985), due to the reform and opening-up and the household contract responsibility system,[3] the value of AFAF and the amount of pollutant discharges simultaneously increased; thus, the discharge intensity slightly changed. During the period of the 7th FYP and 8th FYP (1986–1995), the state gradually reformed the unified purchase and distribution system of major agricultural products into a system based on planning as the principal and market regulation as the subsidiary, thereby fully mobilizing the enthusiasm of most agricultural producers (Lu and Xie, 2018). The growth rate of AFAF exceeded the pollutant discharge, and the discharge intensity decreased. During the period of the 9th FYP and 10th FYP (1996–2005), agricultural policies were mainly characterized by protecting agricultural production, supporting an increase in farmers' income, promoting agricultural development, and canceling agricultural tax and feeding agriculture by industry; subsequently, the value of AFAF and the amount of pollutant discharges steadily increased, while the discharge intensity remained basically unchanged. During the period of the 11th FYP and 12th FYP (2006–2015), the issue of "agriculture, rural and farmers" has become the top priority of agricultural modernization. The No. 1 Document of the Chinese Central Government focused on the theme for 14 consecutive years, especially with the introduction of a series of new agricultural policies, such as increasing agricultural subsidies, realizing agricultural modernization, and promoting the supply-side structural reform of agriculture, which activated the intrinsic vitality of rural and agricultural development (Cai et al., 2017; Zhao et al., 2016). The growth rate of AFAF once again exceeded the pollutant discharges, and the discharge intensity decreased.

The end years of each FYP are also selected to reveal the spatial and temporal pattern of the discharge intensity. To enhance the comparability across different years, all values of the discharge intensity of COD, TN and TP are considered in logarithm, and the natural break point was used to divide the intensity into five grades as shown in Appendix 2. The strength diminished from the 1st grade to the 5th grade. Notably, Tibet and Qinghai belong to plateau pastoral areas. The numbers of cattle and sheep were large, and the value of AFAF was very small; thus, the discharge intensities were very high. Considering that animal husbandry is their main pollution source and the resulting pollution is mainly absorbed by grassland, the pollution mechanism completely differs from that in traditional agricultural areas; thus, the two provinces cannot be compared in a comparative analysis in this study.

During the period of the 5th FYP and 6th FYP, there was minimal difference in the level of socioeconomic development. The discharge intensities in most provinces were dominated by the 3rd and 4th grades, except for the northeast and southeast coastal areas. During the period of the 7th FYP and 8th FYP, the agricultural production structure and rural economic structure tended to be diversified. The discharge intensity in most provinces was reduced to the 2nd and 3rd grades, the discharge intensity of COD gradually decreased from east to west, the spatial law of the discharge intensity of TN was not obvious, and the discharge intensity of TP gradually decreased from north to south. During the period of the 9th FYP and 10th FYP, the social and economic development in rural areas slowed; the discharge intensity in most provinces remained at the 2nd and 3rd grades; and the overall pattern changed only slightly. During the period of the 11th FYP and 12th FYP, the policy effect of the "cancelation of agricultural tax and industry to feed agriculture" was highlighted. The discharge intensity in most provinces decreased to the 2nd and 1st grades, and the same spatial variation law as that in the 7th FYP and 8th FYP was observed.

Over the last 40 years, due to the influence of land system reform and economic environment and agricultural policy, the discharge intensity showed a phasic pattern consistent with the national economic plan. It

[2] To progress the socialist economy in a planned way, China started the five-year plan in 1953. Due to some noneconomic factors, the plans were often interrupted during the 1953–1978 period. Generally, 1976–1980 was the 5th Five-Year Plan, and currently, China is in the 13th Five-Year Plan.

[3] The household contract responsibility system is a basic economic system in China's rural areas in which farmers contract land from rural collective economic organizations in family units and enjoy the planting incomes but pay a certain amount of agricultural tax.

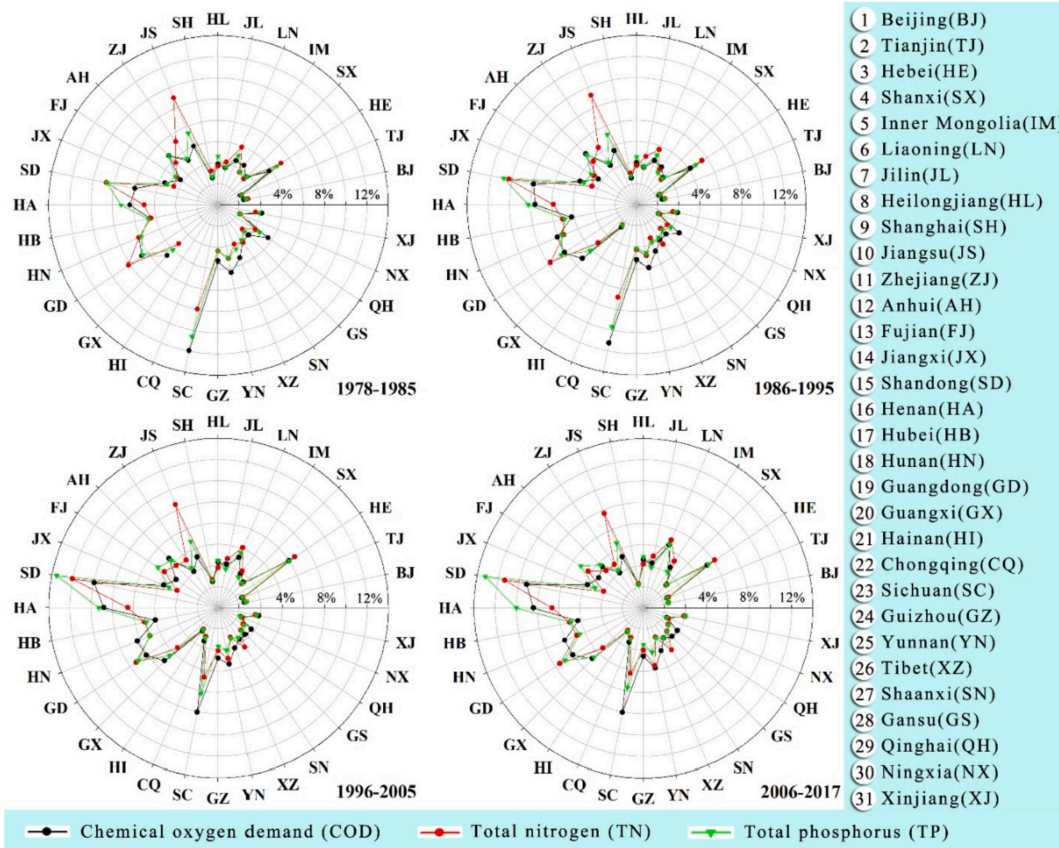


Fig. 4. Percent contributions to COD, TN and TP in different provinces in China. The value is % and represents the percent contribution to a pollutant in a province to the total amount of that pollutant.

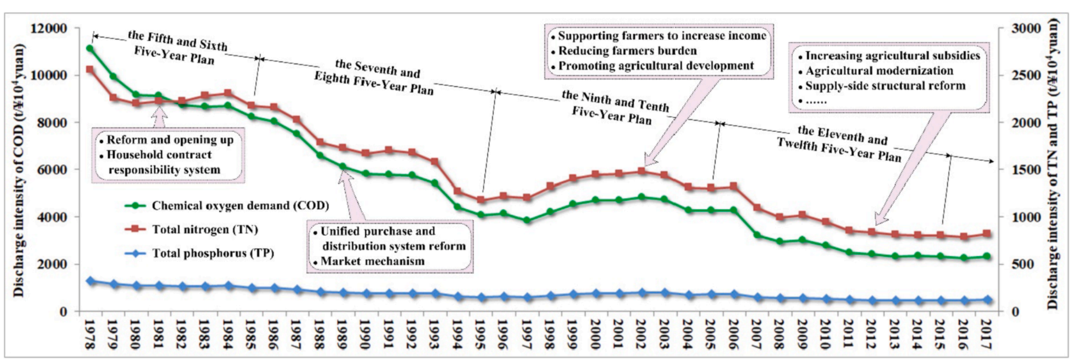


Fig. 5. Variation characteristics of the discharge intensity of COD, TN and TP during the 1978–2017 period in China. The y-axis on the left represents the discharge intensity of COD, and the y-axis on the right represents the discharge intensity of TN and TP.

can be inferred that the national policy was an indicator of the discharge intensity of ANPSP. If some positive incentives are applied, such as implementing market mechanisms and increasing agricultural subsidies, the discharge intensity was reduced (Wu and Ge, 2019); otherwise, if some type of negative incentives are applied, such as increasing agricultural taxes, the discharge intensity was increased (Rao et al., 2012). On the spatial scale, because of the differential in the regional natural environment, the socioeconomic level, the agricultural planting structure and the intensive agricultural degree, the spatial pattern of the discharge intensity was related to the agricultural conditions (Yang and Lin, 2019). This finding fully shows that the scale of agricultural production is the main factor determining the total amount of pollutants.

4. Conclusions

This study uses an inventory analysis to estimate the ANPSP loads from 1978 to 2017 in China. Over the past 40 years, due to an increase in livestock and poultry breeding, large rural populations, and application of mineral fertilizers, the pollution loads of COD, TN, TP increased by 91.0%, 196.2%, and 244.1%, respectively. The total pollution loads showed a staged growth trend, including a free development stage, reform promotion stage, market regulation stage and policy incentive stage. The results of the pollution source analysis showed that the contributions of mineral fertilizers, livestock and poultry breeding, aquaculture, farmland straw and rural household waste to pollution loads greatly varied during different periods, but the main sources of COD, TN and TP remained basically unchanged. Livestock and poultry breeding and rural household waste were the main sources of COD, and their total percent contribution decreased from 96.6% to 83.1% during the 1978–2017 period. Mineral fertilizers and livestock and poultry breeding were the main sources of TN, and their total percent contribution slightly decreased from 73.0% to 72.3% during the 1978–2017 period; however, the highest value was 80.8% in 1995. The main source of TP changed from livestock and poultry breeding and rural household waste to livestock and poultry breeding and mineral fertilizers, and their total percent contribution decreased from 88.4% to 69.1% during the 1978–2017 period. Shandong, Guangdong, Sichuan, and Henan were the top producers of ANPSP loads, and their COD, TN, and TP loads accounted for approximately 32%, 30%, and 35% of the national totals, respectively. Under the encouragement of national policies, the discharge intensity of COD, TN and TP decreased by 79.2%, 67.8%, and 62.6%, respectively. The discharge intensity of ANPSP loads also exhibited a phasic feature aligned with the national economic plan, and its spatial variation was mainly determined by the agricultural conditions. Our results suggest that China agriculture still face severe pollution loads with obviously sources. China's agricultural policies relevantly reduce the pollution discharge intensity. In the future, agricultural pollution loads and driving mechanisms in the important economic areas should be emphasized, such as Yangtze River delta, Pearl River Delta and Bohai region. Moreover, resources utilization patterns and corresponding environmental effects under different rural development stages also needs to clarify.

Competing interests

The authors declare no competing interests.

Author statement

This paper reports on our original work without plagiarism, and all works of others has been appropriately cited; This paper has disclosed the financial support without any conflicts of interest.

Acknowledgements

This research was financed by the Key Program of the National Natural Science Foundation of China (Grant No.41931293&41731286), and the National Natural Science Foundation of China (Grant No. 41601599).

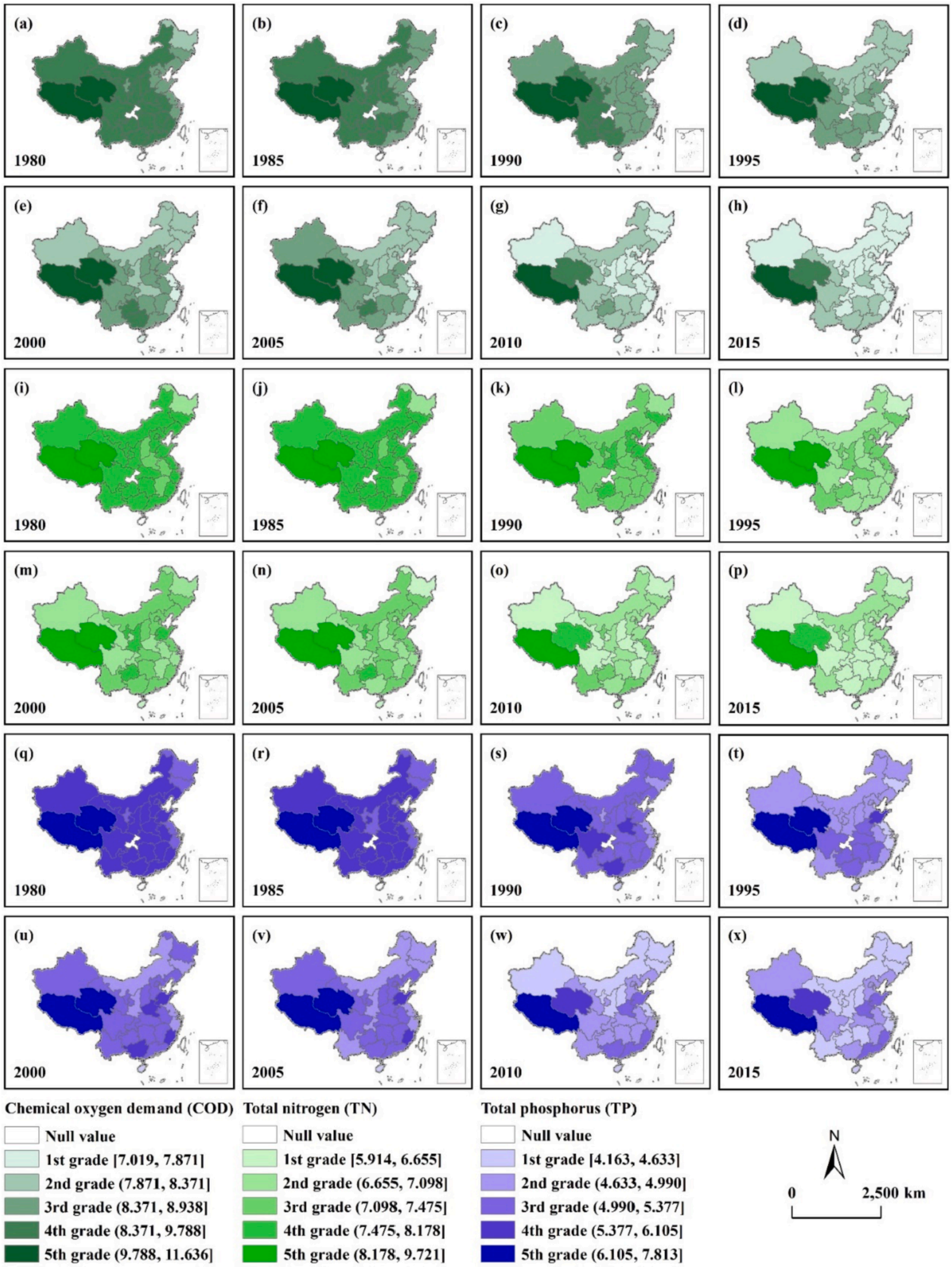
Appendix 1

Provincial pollutant production and discharge of livestock and poultry breeding in China in 2002.

Province	Pollutant production			Pollutant-discharge coefficient			Pollutant discharge		
	COD	TN	TP	COD	TN	TP	COD	TN	TP
Beijing	54.00	8.76	3.06	27.6	24.4	21.2	14.90	2.14	0.65
Tianjin	42.53	6.44	2.00	24.45	20.8	17.15	10.40	1.34	0.34
Hebei	527.99	79.51	20.65	24.45	20.8	17.15	129.09	16.54	3.54
Shanxi	124.46	19.36	4.08	18.15	13.6	9.05	22.59	2.63	0.37
Inner Mongolia	197.11	34.72	7.31	18.15	13.6	9.05	35.78	4.72	0.66
Liaoning	235.12	36.68	10.73	24.45	20.8	17.15	57.49	7.63	1.84
Jilin	285.35	45.48	11.52	18.15	13.6	9.05	51.79	6.19	1.04
Heilongjiang	271.10	40.68	8.81	18.15	13.6	9.05	49.21	5.53	0.80
Shanghai	42.77	6.89	2.68	27.6	24.4	21.2	11.80	1.68	0.57
Jiangsu	242.57	36.47	13.14	18.15	13.6	9.05	44.03	4.96	1.19
Zhejiang	121.13	15.90	5.59	24.45	20.8	17.15	29.62	3.31	0.96
Anhui	407.04	60.98	15.55	24.45	20.8	17.15	99.52	12.68	2.67
Fujian	136.69	18.61	5.76	27.6	24.4	21.2	37.73	4.54	1.22
Jiangxi	270.04	38.53	10.19	27.6	24.4	21.2	74.53	9.40	2.16
Shandong	751.76	121.08	32.62	27.6	24.4	21.2	207.49	29.54	6.92
Henan	826.03	123.82	28.64	24.45	20.8	17.15	201.96	25.75	4.91
Hubei	330.12	46.16	12.46	24.45	20.8	17.15	80.71	9.60	2.14
Hunan	528.30	68.93	19.26	27.6	24.4	21.2	145.81	16.82	4.08
Guangdong	429.92	66.14	20.66	27.6	24.4	21.2	118.66	16.14	4.38
Guangxi	462.67	65.65	14.97	24.45	20.8	17.15	113.12	13.65	2.57
Hainan	81.63	12.50	2.81	18.15	13.6	9.05	14.82	1.70	0.25
Chongqing	164.10	21.58	6.05	18.15	13.6	9.05	29.78	2.94	0.55
Sichuan	774.67	106.44	26.16	24.45	20.8	17.15	189.41	22.14	4.49
Guizhou	346.46	50.18	9.84	18.15	13.6	9.05	62.88	6.82	0.89
Yunnan	424.18	60.48	12.86	18.15	13.6	9.05	76.99	8.23	1.16
Tibet	240.24	39.39	6.64	27.6	24.4	21.2	66.31	9.61	1.41
Shaanxi	154.07	23.07	4.98	18.15	13.6	9.05	27.96	3.14	0.45
Gansu	191.60	29.63	5.79	18.15	13.6	9.05	34.78	4.03	0.52
Qinghai	177.75	29.57	5.12	27.6	24.4	21.2	49.06	7.21	1.08
Ningxia	35.48	5.93	1.25	18.15	13.6	9.05	6.44	0.81	0.11
Xinjiang	200.36	36.83	6.99	24.45	20.8	17.15	48.99	7.66	1.20
Total	9077.24	1356.35	338.16				**2143.63**	**269.08**	**55.12**

Note: Pollutant discharge is recalculated by using this study's pollutant production and Lai's pollutant-discharge coefficients. The values of the pollutant production and discharge are 10^4t, and the pollutant-discharge coefficients cited by Lai and their values are presented in percentage to refer to the proportion of pollutants discharged into the environment.

Appendix 2. Spatiotemporal patterns of the discharge intensity of COD (a-h), TN (i-p) and TP (q-x) in typical years in China



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