Net anthropogenic phosphorus inputs (NAPI) index application in Mainland China

Yuguo Han^{a,*}, Xinxiao Yu^a, Xiaoxue Wang^b, Yunqi Wang^a, Jinxia Tian^c, Lei Xu^d, Chengzhi Wang^e

^a School of Soil and Water Conservation, Beijing Forestry University, Beijing 100083, China

^b State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China

^c Beijing Water Technology Center, Beijing 100073, China

^d China Irrigation and Drainage Development Center, Beijing 100054, China

^e Water Service Bureau of Chaoyang of Beijing, Beijing 100026, China

HIGHLIGHTS

- ▶ We studied phosphorus input more reasonable by taking seeding P into consideration.
- ▶ We analyzed spatial and temporal variation of phosphorus input in Mainland China.
- ▶ We analyzed the main components of net P input and their change.
- ▶ Fertilize phosphorus is the largest source of net anthropogenic phosphorus input.
- ▶ The primary factor of net anthropogenic phosphorus input change is total population.

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ABSTRACT

This study provides a new understanding on sources of P, which may serve as a foundation for further exploration of anthropogenic effects on P input. Estimation of net anthropogenic phosphorus input (NAPI) was based on an inventory of phosphorus (P) fertilizer use, consumption of human food and animal feed, seeding phosphorus and non-food phosphorus net flux. Across Mainland China, NAPI had an upward trend from 1981 to 2009, which reflects development trend of the population and economic. NAPI for years 1981, 1990, 2000 and 2009 are $190 \text{ kg P km}^{-2} \text{ yr}^{-1}$ ($1.8 \text{ kg P per person yr}^{-1}$), $295 \text{ kg P km}^{-2} \text{ yr}^{-1}$ ($2.5 \text{ kg P per person yr}^{-1}$), $415 \text{ kg P km}^{-2} \text{ yr}^{-1}$ ($3.1 \text{ kg P per person yr}^{-1}$) and $465 \text{ kg P km}^{-2} \text{ yr}^{-1}$ ($3.4 \text{ kg P per person yr}^{-1}$), respectively. On a geographical basis, NAPI per unit area is lower in northwest Mainland China than in southeast Mainland China with the largest NAPI of $3101 \text{ kg P km}^{-2} \text{ yr}^{-1}$ in Shanghai, while NAPI per person is in reverse with the largest NAPI $7.7 \text{ kg P per person yr}^{-1}$ in Tibet. P input of fertilizer is the largest source of NAPI, accounting for 57.35–83.73% ($109\text{--}390 \text{ kg P km}^{-2} \text{ yr}^{-1}$) of the total NAPI, followed by non-food P and P in human food and animal feed. Year 2000 was a critical point where P changed almost from net input to output. Grain production rate per unit mass of fertilizer showed an obvious downward trend. The primary factor in relation to the change in NAPI is total population.

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1. Introduction

Regional nutrient pollution is divided into point source pollution and non-point source pollution. Point source pollution is generated from sewage outlets, so it is relatively easy to identify and control. Non-point source pollution has complicate formation process, spatial variability, long latent cycle, and so on (Straalen and Gestel, 2008), and its severity is being gradually revealed in re-

cently years. China is one of the countries in the world with rapidest population and economy growth. In the past thirty years, population and economy growth has brought about many environmental issues (Hu et al., 2011a, 2011b; Wu et al., 2011), among which the nutrient non-point source pollution is a relatively serious one. Even though some technology has been used to control nutrient non-point source pollution, the effect is imperceptible because the control actions have been merely focused on end-control engineering projects, such as establishment of sewage farm, artificially-reclaiming of wetland at bayou or watercourse (Liu et al., 2010; Guan et al., 2011). Therefore, investigation on pollutant sources and implementation of source-control policies is indispensable.

* Corresponding author. Address: School of Soil and Water Conservation, Beijing Forestry University, 35 Qinghua Donglu, Handian District, P.O. Box 65, Beijing 100083, China. Tel./fax: +86 10 62336324.

E-mail address: yghan@bjfu.edu.cn (Y. Han).

Eutrophication is a kind of water pollution caused by excessive nutrients. Phosphorus (P) is one of the main pollution elements of eutrophication. P emission from different pathways and sources is a key issue concerning the protection of water quality and sustainable watershed management practices (Lowrance et al., 1985; Rivera et al., 2007; Neset et al., 2008).

The nutrient input to the watershed is mainly caused by human activities (Leeben et al., 2008), such as crop cultivation, livestock breeding, human excretion, household garbage and so on. Many researchers have focused their attention on the evaluation of pollutant loadings by human activities. Jordan and Weller (1996) put forth the concept of net anthropogenic nitrogen input (NANI), which refers to the difference between the total amount of N produced from applied fertilizer, N fixation and atmospheric deposition and the total amount of N exported from food and feed in the watershed ecosystem. The study of McIsaac et al. (2001) shows that NANI is more sensitive to the N flux in the watershed, i.e. a slight change in NANI may result in a great change in riverine N content. Russell et al. (2008) also conducted a relevant investigation on net anthropogenic phosphorus input (NAPI = P Fertilizer + P Feed + P Food + Non-food P), pointing out that NAPI is an important index for predicting the P pollution in watershed. The theories provide useful research methods for investigation on nutrient input (Bristow et al., 2008; Kelderman et al., 2009; Li et al., 2011; Obour et al., 2011; Han et al., 2011). In addition, nutrient element in seed is always mentioned in researches on agricultural nutrient balance, but it is seldom taken into consideration in NAPI research (OECD, 2001; Feng and Fang, 2006; Fang et al., 2007). Therefore, we introduced a comparatively reasonable way of studying P input by taking P in seed into consideration, that is, $NAPI = P \text{ fertilizer use} + P \text{ in seed} + P \text{ in human food and animal feed} + \text{non-food P}$.

The purpose of this paper is to calculate net anthropogenic phosphorus budgets in Mainland China, which includes: (a) researching the spatial distribution and temporal variation of net P input; (b) analyzing the main components of net P input and their change; and (c) discussing the relationship between the typical socioeconomic factors and net P input. To some extent, this paper overcomes the difficulties in quantifying P sources and introduces a more reasonable way for studying P input.

2. Methods

2.1. Study sites

China is the fourth largest country in the world (after Russia, Canada, and the USA). It is situated at 4° to 53°30' North Latitude and 73°40' to 135°05' East Longitude and is bordered by Russia, India, Afghanistan, Bhutan, Myanmar, Kazakhstan, North Korea, Kyrgyzstan, Laos, Macau (semi-autonomous), Mongolia, Nepal, Pakistan, Tajikistan, and Vietnam. China covers about 9.6×10^6 square km. The population of China is about 13.7×10^8 (as of December, 2010). With highlands in the west and plains in the east, from the Tibetan Plateau and other less-elevated highlands rise rugged east–west trending mountains, and plateaus interrupted by deep depressions fanning out to the north and east. China is composed of 23 provinces, 5 autonomous regions, 4 municipalities, and 2 special administrative regions. The study region in this paper is Mainland China, namely, Taiwan province, Hongkong and Macao special administrative regions are excluded. Therefore, with each administrative region as a research unit, there are 31 research units in total (see Fig. 1 and Table 1).

We obtained the data from the National Bureau of Statistics of China. Land cover was derived from satellite images of Ministry of Land and Resources of the People's Republic of China. We calculated net P input values for years 1981, 1990, 2000 and 2009.

2.2. NAPI estimation approach

NAPI was estimated by accounting for the anthropogenic P input in each unit. We quantified input of P in each unit, most of which are derived from human activities: fertilizer use, seeding, human food and animal feed, and non-food P.

2.2.1. P fertilizer use

Current management practices in agricultural production are highly dependent on intensive fertilizer use, so fertilizer use is one of the important sources of NAPI. We obtained data on the amount of applied P fertilizer within each research unit from the National Bureau of Statistics of China. Estimates of fertilizer application are available for each research unit. P fertilizer contains 12%–18% of P_2O_5 (Liang, 1999; Gao et al., 2001). Total P fertilizer application was converted to kg P by multiplying by 436.4 kg P per ton P_2O_5 .

2.2.2. Seeding P

We chose vegetable and seven main agricultural crops to estimate seeding P in each research unit. The vegetable was represented by cabbage since the value of seeding P was slightly different between different kinds of vegetable. Seeding P per unit area for each crop type has been reported by Agricultural Technology Promotion Center of China (1999) (see Table 2). The data on cultivation area of each crop type were obtained from the National Bureau of Statistics of China. Seeding P was estimated by multiplying P input of seed per unit area for each crop type by cultivation area in each research unit.

2.2.3. Net P input in human food and animal feed

Humans and animals require a great deal of food and feed during their lives, so net P in human food and animal feed is also an important component of NAPI. Human food and animal feed are associated with input/output P of agricultural products. With a few exceptions, we used the general method introduced by Jordan and Weller (1996), who quantified the net input of P as:

net input in food and feed = food and feed consumption of human and animal – animal production for human consumption – crop production.

We obtained data on human population and crop and animal production from the National Bureau of Statistics of China. Each item, as well as the final result, in this method is presented by research unit data.

2.2.3.1. Food and feed consumption. Human consumption of P in food was estimated by multiplying the number of inhabitants in each research unit (see Table 2) by per capita intake of 0.52 kg P per year (Wu, 2005). P consumption per individual animal was then multiplied by the number of each animal type in each research unit. We chose the values of consumption as reported by Wu Shuxia (2005) and the values of the percentage P excreted as reported by van (1998). We assumed all animals were completely formula fed, i.e., 80% from corn and 20% from pasture (Li, 2007).

2.2.3.2. Crop production. We chose vegetable and 14 main agricultural crops to estimate P production in each research unit. The vegetable was represented by cabbage since phosphorus content was slightly different between different kinds of vegetable. We calculated P content in the crop harvest in each research unit. P content ($g \text{ kg}^{-1}$) for each crop type has been reported by Wang (2003) (see Table 2). We assumed that pests, spoilage, and processing caused a 10% loss for all crops (Jordan and Weller, 1996).

Fig. 1. Geographic location of Mainland China. This figure presents the distribution of the 31 research units in Mainland China, which are divided by dark black outlines.

2.2.3.3. Animal production. The animal P production category includes meat, milk, eggs, etc. We estimated animal P production as the difference between animal feed consumption (intake) and animal excretion (waste production). We assumed that spoilage and inedible components caused a 10% loss of animal products available for consumption.

2.2.4. Non-food P

Non-food P mainly comes from the detergent in people's daily life. In China, the sewerage emission is 150 L per person per day (Shang, 2009; Zhang, 2010). As Shang (2009) measured, concentration of the total P in Mainland China household sewage was 21 mg L⁻¹. There are 365 d in 1 year, so the P discharged from household sewage is 1.15 kg per person per year. As P discharged from human excretion was 0.52 kg per person per year, the rest P, i.e., non-food P was 0.63 kg per person per year.

2.3. Data analysis

2.3.1. Analysis of NAPI

Based on P fertilizer use, P in human food and animal feed, seedling P and non-food P, NAPI was calculated by summing the values for all research units within Mainland China. Geographic and spatial analysis of NAPI was conducted using average NAPI values in the 31 research units for years 1981, 1990, 2000 and 2009. The land cover data was used with the ArcInfo 9.3 (ESRI Inc.) geographic information system to calculate the proportion of row crops and forest in each unit, while the number of animal in each unit was calculated from agricultural census data. We also investigated differences in NAPI and in its components between different years.

2.3.2. Grey relational analysis

Gray System Theory (GST) gradually developed from requirements for new methods to solve certain problems for solving the complicated interrelationships among the multiple performance characteristics (Deng, 1989). Grey Relational Analysis (GRA) is one of GST. GRA uses the gray relational coefficient (GRC) to describe the trend relationship between an objective series and a reference series at a given point in a system. For a given reference sequence and a given set of comparative sequences, GRA can be used to determine the gray relational grade (GRG) between the reference and each comparative sequence in the given set. Grey relational generating is a process of transferring the original sequence to a comparable sequence. For this purpose, the experimental results are normalized in the range between zero and one (Lin, 2004).

Grey relational grade analysis was conducted between the socioeconomic factors (gross domestic product, gross agricultural output value, cultivated land area, total population density, agricultural population density, the total fertilizer, total population and total grain yield) and NAPI calculation in this paper. GRA was analyzed with the GM v2.1 (Nanjing University of Aeronautics and Astronautics).

3. Results

3.1. Spatial variation of NAPI

The geographic differences of NAPI average for years 1981, 1990, 2000 and 2009 in Mainland China was investigated (see Fig. 2). NAPI per unit area is lower in northwest Mainland China than in southeast Mainland China (see Fig. 2a) and NAPI per person exactly reverses NAPI per unit area (see Fig. 2b) since NAPI is in

Table 1
Characteristics of Mainland China.

Name	Area (10 ⁴ km ²)	Population (10 ⁴)			
		1981	1990	2000	2009
Beijing	1.68	902.00	1087.00	1382.00	1755.00
Tianjin	1.13	763.00	883.00	1001.00	1228.16
Hebei	19.00	5256.00	6028.00	6744.00	7034.40
Shanxi	15.60	2509.00	2818.00	3297.00	3427.36
Inner Mongolia	118.30	1903.00	2111.00	2376.00	2422.07
Liaoning	14.57	3535.00	3998.00	4238.00	4319.00
Jilin	18.70	2231.00	2515.00	2728.00	2739.55
Heilongjiang	46.90	3239.00	3477.00	3689.00	3826.00
Shanghai	0.62	1163.00	1351.00	1674.00	1921.00
Jiangsu	10.26	6010.00	6817.00	7438.00	7725.00
Zhejiang	10.18	3871.00	4084.00	4677.00	5180.00
Anhui	13.90	4956.00	5629.00	5986.00	6131.00
Fujian	12.00	2557.00	3061.00	3471.00	3627.00
Jiangxi	16.66	3304.00	3828.00	4140.00	4432.16
Shandong	15.30	7395.00	8343.00	9079.00	9470.30
Henan	16.70	7397.00	8614.00	9256.00	9487.00
Hubei	18.74	4740.00	5476.00	6028.00	5720.00
Hunan	21.00	5360.00	6060.00	6440.00	6406.00
Guangdong	18.60	5884.00	6321.00	8642.00	9638.00
Guangxi	23.63	3613.00	4253.00	4489.00	4856.00
Hainan	3.40	565.05	642.00	787.00	864.07
Chongqing	8.20	2685.45	2878.39	3090.00	2859.00
Sichuan	48.80	7238.55	7758.61	8329.00	8185.00
Guizhou	17.00	2827.00	3273.00	3525.00	3798.00
Yunnan	39.40	3223.00	3675.00	4288.00	4571.00
Tibet	122.00	186.00	222.00	262.00	290.03
Shaanxi	20.50	2865.00	3247.00	3605.00	3772.00
Gansu	45.00	1941.00	2293.00	2562.00	2635.46
Qinghai	72.00	382.00	443.00	518.00	557.30
Ningxia	6.64	383.00	466.00	562.00	625.20
Xinjiang	160.00	1303.00	1537.00	1925.00	2158.63

This table presents the research units. The area is indicated in ten thousands km²; and the population was collected in 1981, 1990, 2000, 2009 and is indicated in ten thousands.

relation to population density and agriculture land area. Northwest Mainland China is mainly covered by forest and desert (see Fig. 2c), where NAPI per unit area is relatively lower, while southeast Mainland China is mainly covered by agricultural and developed land, where NAPI per unit area is relatively higher. Southeast Mainland China is a region with rapidly developed economy and thus has a greater population density and a higher gross domestic product (GDP). The study areas focusing on cities generally have a greater

population density and relatively less agriculture land area. Thus, NAPI per person in these areas is lower. In contrast, the study areas focusing on agriculture have a lower population density and larger agriculture land area. Thus, NAPI per person in these areas is higher. Shanghai has the largest NAPI of 3101 kg P km⁻² yr⁻¹ (see Fig. 2a), and Tibet has the largest NAPI 7.7 kg P per person yr⁻¹ (see Fig. 2b). Over the past 28 years, the average NAPI was 341 kg P km⁻² yr⁻¹ or 2.7 kg P per person yr⁻¹ in Mainland China.

3.2. Temporal variation of NAPI

NAPI for different years in Mainland China is investigated (see Table 3). Across Mainland China, the largest NAPI value (465 kg P km⁻² yr⁻¹, 3.4 kg P per person yr⁻¹) appeared in 2009. Over the past 28 years, NAPI per unit area had an upward trend in the 31 research units, which reflects development trend of population and economic. NAPI per person had an upward trend in most research units except Beijing, Liaoning, Jilin, Shanghai, Tibet and Qinghai. Such difference was mainly caused by NAPI quantity and population. Over the past 28 years, cultivated area of Mainland China increased from 9.9×10^5 km² to 12.2×10^5 km², while fertilizer use quantity increased from 133×10^5 ton to 539×10^5 ton and meanwhile population increased from 9.9×10^8 to 13.2×10^8 . Therefore, NAPI quantity had a rising trend. As for NAPI per unit area, Henan (2675 kg P km⁻² yr⁻¹) had a greatest change over the last 28 years, followed by Tianjin (1615 kg P km⁻² yr⁻¹) and Hubei (1402 kg P km⁻² yr⁻¹). As for NAPI per person, Xinjiang (6.5 kg P per person yr⁻¹) had a greatest change, followed by Henan (4.3 kg P per person yr⁻¹) and Hubei (4.3 kg P per person yr⁻¹).

3.3. Change in NAPI sources

The sources of NAPI in Mainland China in different years were analyzed (see Fig. 3). P input of fertilizer is the largest source of NAPI, followed by non-food P. P fertilizer use had an upward trend from 57.35% (109.12 kg P km⁻² yr⁻¹) to 83.73% (389.58 kg P km⁻² yr⁻¹) of NAPI from 1981 to 2009, and meanwhile cultivated area increased only from 9.90×10^5 km² to 12.17×10^5 km². As can be seen, fertilizer use per unit area had a sharp increase.

Non-food P is closely related to population. Since population has been increasing, non-food P input increased from 66.02 kg P km⁻² yr⁻¹ in 1981 to 87.25 kg P km⁻² yr⁻¹ in 2009.

Table 2
Data and values of NAPI subentry.

Input of seeding P			Animal and human P consumption and excretion (Van, 1998; Wu, 2005)					P content in agricultural crop products (Wang, 2003)			
Seed type	Seeding P (g kg ⁻¹)	Seeding P (kg hm ⁻²)	Animal type	Waste production (P excretion, kg P individual ⁻¹ yr ⁻¹)	Percent excreted (%)	Consumption (P intake rate, kg P individual ⁻¹ yr ⁻¹)	Animal production (kg P individual ⁻¹ yr ⁻¹)	Crop type	P (g kg ⁻¹)	Crop type	P (g kg ⁻¹)
Paddy	1.82	6.43	Hog and pig	3.17	69	4.59	1.42	Corn	2.44	Chestnut	0.89
Wheat	3.02	23.81	Horse and cattle	9.78	89	10.99	1.21	Wheat	1.88	Apples	0.12
Corn	2.54	4.53	Chicken	0.12	65	0.18	0.06	Soybeans	4.65	Grapes	0.13
Soybean	4.91	8.90	Duck	0.22	65	0.34	0.12	Paddy	1.10	Peaches	0.14
Broomcorn	3.29	5.96	Sheep and lamb	1.06	84	1.26	0.20	Millet	2.99	Pears	0.13
Peanut	0.32	0.58	Human	0.52	100	0.52	–	Broomcorn	3.29	Watermelon	0.12
Cotton	0.22	0.04						Peanuts	2.50	Vegetable	0.30
Vegetable	0.34	0.03						Potatoes	0.40		

The data of waste production are based on Wu's research, and the data of percent excreted are based on Van's research. Consumption is obtained by dividing Waste production by Percent excreted, and Animal production is estimated as Consumption minus Waste production.

Fig. 2. Average NAPI in each unit for 1981, 1990, 2000 and 2009 and land use type in each research unit in 2000. The black outlines indicate the boundary of the units. The land use is classified as forest land, agriculture land, grass land, developed land, river and other land.

Table 3
NAPI for different years.

Name	NAPI per unit area ($\text{kg P km}^{-2} \text{yr}^{-1}$)					NAPI per person ($\text{kg P per person yr}^{-1}$)				
	1981	1990	2000	2009	Difference between 1981 and 2009	1981	1990	2000	2009	Difference between 1981 and 2009
Beijing	931	717	1108	1361	430	1.7	1.1	1.3	1.3	−0.4
Tianjin	849	824	1593	2464	1615	1.3	1.1	1.9	2.4	1.1
Hebei	495	794	1260	1300	804	1.8	2.5	3.5	3.5	1.7
Shanxi	281	505	732	690	409	1.8	2.8	3.5	3.2	1.4
Inner Mongolia	32	40	66	119	87	1.9	2.2	3.2	5.7	3.7
Liaoning	492	560	569	564	72	2.1	2.1	2.0	1.9	−0.1
Jilin	181	134	170	147	−34	1.6	1.3	1.2	1.0	−0.5
Heilongjiang	91	153	273	345	255	1.3	2.0	3.4	4.1	2.8
Shanghai	2950	2403	2895	3101	152	2.1	1.5	1.4	1.3	−0.8
Jiangsu	1210	1387	2089	2439	1229	2.2	2.2	3.0	3.4	1.2
Zhejiang	714	836	854	972	259	1.9	2.2	1.9	2.0	0.0
Anhui	615	1233	1597	1411	796	1.7	3.1	3.7	3.2	1.5
Fujian	399	653	833	909	510	1.9	2.7	3.0	3.1	1.2
Jiangxi	328	635	710	785	457	1.7	2.8	2.9	3.0	1.3
Shandong	947	1235	1928	1742	796	2.0	2.3	3.3	2.9	0.9
Henan	665	1678	2858	3340	2675	1.5	3.2	5.1	5.8	4.3
Hubei	424	912	1445	1826	1402	1.7	3.1	4.5	5.9	4.3
Hunan	493	636	705	767	274	2.0	2.2	2.3	2.5	0.6
Guangdong	653	796	895	1145	492	2.0	2.3	1.9	2.1	0.1
Guangxi	288	458	606	702	414	1.9	2.6	3.2	3.4	1.5
Hainan	295	442	487	696	401	1.9	2.4	2.2	2.9	1.0
Chongqing	512	744	1063	1075	564	1.6	2.1	2.8	3.1	1.5
Sichuan	242	341	491	570	328	1.6	2.1	2.9	3.4	1.8
Guizhou	269	381	441	459	190	1.7	2.1	2.2	2.1	0.5
Yunnan	144	241	319	394	250	1.7	2.5	2.9	3.3	1.6
Tibet	13	14	15	19	6	8.3	7.6	7.0	8.0	−0.3
Shaanxi	216	322	491	547	331	1.6	2.0	2.8	3.0	1.4
Gansu	85	166	268	235	150	1.8	2.9	4.2	3.6	1.8
Qinghai	26	31	29	30	3	4.9	5.1	4.1	3.8	−1.1
Ningxia	145	187	345	421	276	2.0	2.1	3.2	3.5	1.5
Xinjiang	18	31	61	113	95	2.3	3.4	5.3	8.7	6.5
Mainland China	190	295	415	465	275	1.8	2.5	3.1	3.4	1.5

However, its percentage to the total input decreased (from 34.69% to 18.75%) mainly due to more rapid increase of NAPI.

Net P in human food and animal feed is proportional to the human population and animal numbers. The positive percentage values of P for human food and animal feed indicate that P input occurs, while the negative percentage values indicate the possible occurrence of P output (see Fig. 3). When dietary demands for P cannot be met by local crop and animal product, it is necessary to import food and feed; otherwise, export of food and feed may be needed. Year 2000 was a critical point where P changed almost from net input to output, indicating that food product could almost satisfy people's demands since then. Over the past 28 years, P in human food and animal feed had a downward trend (from 7.48% to 2.76%).

Seeding P is closely related to cultivated area, so seeding P input increased from $0.91 \text{ kg P km}^{-2} \text{yr}^{-1}$ in 1981 to $1.27 \text{ kg P km}^{-2} \text{yr}^{-1}$ in 2009. However, its percentage to the total input decreased (from 0.48% to 0.27%) mainly due to more rapid increase of NAPI.

4. Discussion

4.1. Relational analysis between the socioeconomic factors and NAPI

Grey relational grade analysis was conducted between the socioeconomic factors (gross domestic product, gross agricultural output value, cultivated land area, total population density, agricultural population density, total fertilizer, total population

Fig. 3. The percentage of each component in NAPI between 1981 and 2009 were analyzed. This figure shows (a) P content of each component and (b) percent of each component in NAPI.

and total grain yield) and NAPI calculation with a discrimination coefficient (ρ) of 0.5. The results are as follows (see Table 4):

$$X_7 > X_4 > X_3 > X_9 > X_5 > X_6 > X_1 > X_2 > X_8$$

The primary factor in relation to the change in NAPI is total population, followed by population density and cultivated land area. Among all of the factors, total population density, agricultural population density and total population are main social factors and their relational grades are 0.992, 0.975 and 0.999, respectively. Total population density has the greatest relational grade, indicating that change in NAPI is mainly determined by the total population density. Cultivated land area, total fertilizer and total grain yield are main agricultural factors and their relational grades are 0.985, 0.972 and 0.982, respectively. As can be seen, cultivated land area has the greatest relational grade, indicating that among the agricultural factors, cultivated land area is a main factor in relation to the change in NAPI. Gross Domestic Product and Gross Agricultural Output Value are main economic factors and their relational grades are 0.897 and 0.839, respectively. Gross Domestic Product has the greatest relational grade, so Gross Domestic Product is the closest economic factor in relation to NAPI change in this study.

4.2. Grain production rate

World-wide agricultural development has proved that fertilizer application is the fastest, most effective and most important means for increasing production. China is an intensive-agriculture country, and agricultural production is highly dependent on fertilizer application (Li et al., 1998; Chen et al., 2007). The cultivated land area in China is 1/7 of the total in the world, but its fertilizer application accounts for 1/3 of the total in the world, ranking first in the world (Chen et al., 2011; Huang et al., 2011; Zhou et al., 2012). In this study, the total grain yield in 2009 was 1.62 times in 1981, while the amount of fertilizer applied was 4.04 times (see Table 4). Grain production rate per unit mass of fertilizer showed an obvious downward trend, indicating that the amount of applied fertilizer per unit weight of grain was gradually increasing, i.e., the fertilizer utilization efficiency was gradually reducing. Low fertilizer utilization efficiency may decline soil fertility, drop crop quality and cause serious environmental pollution (Schroder et al., 2011; Chien et al., 2011). Therefore, it is significant for China to improve fertilizer utilization efficiency in agriculture.

4.3. Method for improving fertilizer utilization efficiency

China is facing harsh problems of growing population, shrinking arable land and increasing food demand. Maximization of fertilizer utilization efficiency is extremely important for food security and ecological environment protection (Hu and Li, 2005; Yan et al., 2008). At present, the main techniques and methods are: 1. Fertilizing accurately in accordance with the farmland nutrients and promoting formulated fertilization technology, that is, based on the rule of fertilizer requirement of crops, soil testing results and fertilizer utilization efficiency, the amount of fertilizer to be applied is adjusted to be reasonable, so that the crops are supplied with comprehensive and reasonable nutrients so as to maximize the potential of crops in increasing yield, thereby improving economic efficiency (Peng et al., 1996, 2002; Gao and Lü, 2006; Liu et al., 2006; He et al., 2007); 2. Developing slow/release fertilizers; slow/release fertilizers can slowly release nutrients necessary for plant growth; they are rich in nutrients, formulated reasonably, pollution-free and long-term effective, and may reduce nutrient loss caused by leaching, fixation or decomposition so as to prevent the crops from premature aging at early stage and de-fertilization at later stage; the nutrients are released no less than 75% within the provided release period; therefore, slow/release fertilizers are considered as the most efficient and convenient measure for reducing fertilizer losses and improving fertilizer utilization efficiency (Zhai et al., 2002; Du et al., 2005); and 3. Improving methods of fertilizing; according to the rule of fertilizer requirement of crops, crops are fertilized reasonably in various growth stages to satisfy the demand for nutrient at each stage so as to achieve the purpose of economic fertilization (Wang, 2002; Lu and Wu, 2004; Jess, 2004; Yu and Zhang, 2006); deep application of fertilizer also needs to be promoted to minimize the loss of fertilizer and improve fertilizer utilization efficiency.

4.4. Fate of NAPI

From the above analysis we can see that there is a huge amount of P input in Mainland China every year. But, where has it gone? Part of it has been deposited in the plant and animal, which is an important mode of P input. Animal and plant cannot survive without P as P is an important component of animal's nucleic acid of genetic material and is involved in plant's photosynthesis and

Table 4

Gross domestic product (X_1)	Gross agricultural output value (X_2)	Cultivated land area (X_3)	Grey relational grade analysis					Grain production rate per unit mass of fertilizer						
			Total population density (X_4)	Agricultural population density (X_5)	Total fertilizer (X_6)	Total population (X_7)	Total area (X_8)	Total grain yield (X_9)	Year	Total fertilizer (10^7 kg)	P fertilizer use (10^7 kg)	Total grain yield (10^7 kg)	Grain production rate per unit mass of fertilizer (kg kg^{-1})	Grain production rate per unit mass of fertilizer P (kg kg^{-1})
Relational grade 0.897	0.839	0.985	0.992	0.975	0.972	0.999	0.787	0.982	1981	1334	102	32502	24	319
									1990	2590	206	44624	17	217
									2000	4146	313	46218	11	148
									2009	5391	370	52658	10	142

By the end of 2009, 53.2% of household sewage in Mainland China was treated by sewage treatment plant (Zhou, 2010). After the treatment, 90% of sewage P was left in the sludge of the sewage treatment plant and would eventually be landfilled. In recent years, researches on re-use of sewage sludge are being conducted (e.g., used as agricultural fertilizer and the production of biogas, etc.), but currently they have not been applied on a large scale (Xiong and Zhang, 2007).

First of all, a reasonable region planning is needed, which may play an obvious role in regulating and controlling P pollution from the perspective of population. As for a reasonable region planning, such as the reasonable population distribution and public transportation system, the key point is to change the existed intensive work and life style, which, however, needs a long time. Secondly, scientific fertilizer application, especially the use of organic fertilizer should be emphasized. The amount, manner and time of the organic fertilizer application should be based on the soil properties, crop growing conditions, properties of the crop in absorbing the nutrition (Liu et al., 2010). Thirdly, the disposal of agricultural wastes such as livestock manure and crop straw should be regulated. P pollution caused by directly abandoned agricultural wastes cannot be ignored as they are rich in organic matter and nutrients. A biological waste management and centralized livestock management should be adopted to prevent P loss in the agricultural surface water. In addition, crop residue and straw play an important practical role in controlling soil erosion, inhibiting nutrient loss and preventing P pollution.

Currently, P diffusion can be effectively controlled by means of ecological engineering. Generally, P diffusion is controlled by inhibiting runoff and increasing infiltration. Many countries are developing a buffer zone to control P pollution, e.g., the vegetative filter zone in the United States and the buffer region in the Briton. After years of experimental studies (Fu et al., 2006), Chengqing Yin has found that multiple-ponds method may prevent up to 94% of P pollution. P pollution can also be effectively controlled by means of combination of engineering measures, biological measures with water and soil conservation through building sand-sinking pool, percolation pond, water catchments and water treatment facility.

This study took a step forward to calculate NAPI in detail on a regional scale, and analyzed its temporal variations and geographic differences. Across Mainland China, NAPI for years 1981, 1990, 2000 and 2009 are $190 \text{ kg P km}^{-2} \text{ yr}^{-1}$ ($1.8 \text{ kg P per person yr}^{-1}$), $295 \text{ kg P km}^{-2} \text{ yr}^{-1}$ ($2.5 \text{ kg P per person yr}^{-1}$), $415 \text{ kg P km}^{-2} \text{ yr}^{-1}$ ($3.1 \text{ kg P per person yr}^{-1}$) and $465 \text{ kg P km}^{-2} \text{ yr}^{-1}$ ($3.4 \text{ kg P per person yr}^{-1}$), respectively. On a geographical basis, NAPI per unit area is lower in northwest Mainland China than in northeast

Mainland China with the largest NAPI of 3101 kg P km⁻² yr⁻¹ in Shanghai, while NAPI per person is in reverse with the largest NAPI 7.7 kg P per person yr⁻¹ in Tibet. P input of fertilizer is the largest source of NAPI, accounting for 57.35–83.73% (109–390 kg P km⁻² yr⁻¹) of the total NAPI, followed by non-food P and P in human food and animal feed. Over the past 28 years, all of the sources of NAPI showed an upward trend. The primary factor in relation to the change in NAPI is total population, followed by population density and cultivated land area. In summary, this study provides a new understanding of sources of P in Mainland China, which may serve as a foundation for further exploration of anthropogenic effects on P input.

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