

The Environmental Consequences of Altered Nitrogen Cycling Resulting from Industrial Activity, Agricultural Production, and Population Growth in China

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Human activities exerted very little effect on nitrogen (N) cycling in China before 1949. Between 1949 and 1999, however, rapid economic development and population growth led to dramatic changes in anthropogenic reactive N, inputted recycling N, N flux on land, N₂O emission, and NH₃ volatilization. Consequently, these changes have had a tremendous impact on the environment in China. In the current study, we estimated the amount of atmospheric wet N deposition and N transportation into water bodies from the watersheds and major valleys in China. Additionally, we addressed issues on leaching and accumulation of NO₃⁻ in the farmland under different climate zones, land use, and cropping systems as well as the potential influence of NO₃⁻ on underground water in China.

KEY WORDS: anthropogenic reactive N, nitrogen flux on land, environment, N₂O, NO₃⁻

DOMAINS: soil systems

INTRODUCTION

Since the 1950s, rapid industrial and agricultural development has occurred in China. As a result, China leads the world in output of major products (such as steel, coal, grain, and meat) and

consumption of coal and synthetic fertilizers[1]. Meanwhile, the size of the population has increased from 0.54 billion in 1949 to 1.26 billion in 1999. This rapid economic development and expansion of the population have brought significant increases in anthropogenic reactive N and recycling N, and alterations of N cycling in watersheds[2,3]. The altered N cycling by human activities has led to increased N transportation into water bodies or escape into the atmosphere[2], which in turn has had significant environmental consequences. In particular, N pollution of water bodies[4] has caused eutrophication. Currently, most of the big lakes in China have stepped into the eutrophic stage[5]. The red tide has occurred more frequently and intensified year by year along the coast of China[6].

The adverse effects on the environment caused by altered N cycling due to increased human activities have already been observed in watersheds of China. China has a vast territory and diverse meteorological conditions ranging from the tropical zone in the south to the cold temperate zone in the north, and from the humid zone in the east to the arid zone in the northwest. Accordingly, crop plantation varies widely among different regions in China. Double- or triple-cropping systems are practiced in the east, the middle, and the south of China. Rice paddy fields account for one fourth of all the cultivated areas. Furthermore, although industrialization in China was initiated in the 1950s, about a century later than in the developed countries, the fast pace of development has far exceeded that of the developed countries. Accordingly, the increased human activities have exhibited a greater adverse impact on N cycling. N cycling and management, and their effects on the environment in the terms of natural and social factors, cropping systems, and the process of the economic development, have attracted tremendous attention from the scientific community.

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METHODS

Calculation of Synthetic N and Fixation N by Legume Crops and Nonsymbiotic N in Paddy Fields

Legume crops in the study included soybean, peanut, pulse, and green manure. The consumption of synthetic N fertilizers, legume crop yields, and the cultivated area of green manure were cited from the *China Agriculture Yearbook*[7] while the essential data from 1949 to 1979 were available in the *Chinese Agriculture Yearbook* of 1980. The amount of fixation N by soybean, peanut, pulse bean, and green manure was calculated according to Zhu[8]. Nonsymbiotic N in paddy fields was calculated using the factor 45 kg N ha⁻¹ year⁻¹ as suggested by Zhu[8].

Calculation of NO_x Formed During Fossil Fuel Combustion

The total consumption of fossil fuel was referred to in the *Chinese Statistic Yearbook*, and the amount of NO_x generated from the fossil fuel combustion was estimated using the conversion factors reported by Wang et al.[9]. Briefly, due to large varieties of fossil fuels and big differences in conversion factors for calculating NO_x emission of the same type of fuels used in different industries, consumption of the fuels by different industries in China were worked out separately on a kind-by-kind basis. And then the NO_x fluxes from combustion of coal, coke, crude petroleum, petrol, diesel oil, kerosene, residual oil, liquefied gas, and natural gas consumed in different industries were figured out and summed up separately according to three categories: coal, petroleum, and natural gas. Eventually, the NO_x flux from the consumption of coal, petroleum, and natural gas between 1949 and 1999 was obtained individually.

Calculation of Excrements N of the Domesticated Animal and Human Populations

The population of animals, such as cattle, horse, ass, mule, camel, swine, sheep, and poultry, and of humans was cited from the *Chinese Agriculture Yearbook* for the corresponding year. The conversion factors were used for calculation according to Xing and Yan[10]. Briefly, excrements N of swine, nondairy cattle, dairy cattle, sheep, poultry, and other domestic animals (horses, ass, mule, and camel) were calculated using the conversion fac-

tors 8, 42, 60, 7, 0.3, and 52 kg N⁻¹ capital⁻¹ year⁻¹, respectively. The excrements N of the human population were calculated by converting the whole human population into the adult population using the conversion factors 0.85 and 5 kg N⁻¹ capital⁻¹ year⁻¹[8].

Calculation of N₂O Emitted from Farmland in China

Direct N₂O emission budget in farmland of China was calculated employing the factors and method suggested by IPCC Phase II methodology[11] and Xing and Yan[10]. Based on data observed at ten year-round monitoring posts scattered all over the country, extrapolation was also used for estimation[12].

Calculation of NH₃ Volatilization in China

The method and conversion factors for the estimation of NH₃ volatilization in China were adopted according to Xing and Zhu[2] as specified in Table 1.

Estimation of Atmospheric Wet N Deposition in China

The amount of atmospheric wet deposition in China was estimated based on mean annual precipitation from 1951 to 1990 and reported data[3,13,14,15]. In more detail, reports from 27 year-round monitoring posts scattered all over the country[13], 2 similar posts in the Shandong Province[14], and 1 in the Qinghai province in western China[15] indicated that the mean value of concentrations of NO₃ and NH₄ in precipitation was 4.36 × 10² mg N m⁻³ and 1.35 × 10³ mg N m⁻³, respectively. The estimation was also based on the data of the mean annual precipitation from 1951 to 1990.

RESULTS AND DISCUSSION

Anthropogenic Reactive N Input in China the Past 5 Decades

Galloway et al.[16] proposed that the increased amount of symbiotic and nonsymbiotic N fixation due to expansion of cultivated areas for legume crops and rice was another source of anthropogenic reactive N. Since China is a major rice grower, we studied the four groups of anthropogenic reactive N includ-

TABLE 1
NH₃ Volatilization Conversion Coefficient

Sources	Emission Factors (kg N kg ⁻¹ N)	References
Animal and human excretia N	0.20	11
Synthetic fertilizer N	Upland: 0.08 for urea and 0.10 for NH ₄ HCO ₃ Paddy field: 0.22 for urea and 0.28 for NH ₄ HCO ₃	2

ing synthetic N fertilizers entering the farm land, NO_x formed during the fossil fuel combustion, symbiotic N fixed by legume crops, and nonsymbiotic N fixed in paddy fields. The variation in the amount of N grouped above was indicated in Table 2.

As shown in Table 2, the amount of anthropogenic reactive N in 1999 was 24 times larger than that in 1949. In the past 50 years, the increase of anthropogenic reactive N was mainly attributed to the large consumption of synthetic N fertilizers and NO_x formed from fossil fuel combustion, especially the former. Consumption of synthetic N fertilizers increased 4000-fold while N mobilized by fossil fuel was 61 times greater than that in 1949. Of the total amount of anthropogenic reactive N in 1999, about 93% was from synthetic N fertilizers and NO_x from the fossil fuel combustion. The situation, however, was the opposite in 1949. N from nonsymbiotic N in rice fields and N fixation by legume crops accounted for 93% while only 7% was from synthetic N fertilizers and NO_x formed during fossil fuel combustion. It was concluded that industrial activities had very little effects on N cycling before 1949. The trend of a significant increase in anthropogenic reactive N started in the early 1980s when N mobilized by synthetic N fertilizers and fossil fuels made up of 85% of the total anthropogenic reactive N in China. These results demonstrate that industrialization is a dominant factor contributing to alterations in N cycling in China.

In contrast, nonsymbiotic N from rice fields decreased steadily from 1975 to 1999 whereas it had increased from 1949 to 1975. The decrease in nonsymbiotic N from rice fields after 1975 corresponds to reduced land areas for rice cultivation. Since the 1980s, the rapid expansion of population has created a dramatically increased demand for food and fibers accompanied by a significant yearly reduction of cultivated area of green manure. This has led to the reduced amount of symbiotic N fixed by legume crops. However, N fixed by legume crops has increased in

a step manner since the 1990s mainly due to the expansion of areas for soybean, peanut, and other legume crops cultivation.

Nitrogen Flux on Land in China the Past 50 Years

According to Howarth et al.[17], only two sources of N were considered to calculate N flux on land in China: the inputted synthetic N fertilizers and excrements N from domestic animals and from humans. Excrement N was a major contributor to recycling N. Like synthetic N fertilizers, it could enter water bodies directly. On the other hand, part of NH₃, NO_x, and N₂O from excrements N could escape into atmosphere and deposit in other ecosystems. The N flux on land calculated on the basis of these two sources could reflect the degree of disturbance of human activities on N cycling and consequently the influence of N on the environment. In the present studies, we estimated the N flux on land in the past 50 years (Table 3) and its distribution in different regions in China.

As shown in Table 3, the N flux on land in China has increased from 586 to 4539 kg N km⁻²year⁻¹ steadily over the past 50 years. The excrements N of animals and of humans accounts for 99.89, 50.00, and 43.88% of the total N flux on land in China in 1949, 1985, and 1999, respectively. Therefore, it has had a significant impact on the environment such as the atmosphere and water bodies.

China has diverse climates and land usage, a high population density, and different levels of economic development among the different regions. In this study, the N flux on land was calculated region by region in accordance with these variables (Table 4).

TABLE 2
Anthropogenic Reactive N in China from 1949 to 1999

Year	Synthetic N	N Fixed by Legume Crop	Nonsymbiotic N from Rice Fields	NO _x from the Fossil Fuel Combustion	Total
	Tg N				
1949	0.006	0.55	0.69	0.08	1.33
1952	0.039	0.77	1.11	0.16	2.08
1957	0.32	0.91	1.28	0.33	2.84
1962	0.49	0.75	1.37	0.58	3.19
1965	1.33	1.15	1.49	0.65	4.62
1970	2.52	1.58	1.62	1.06	6.78
1975	3.40	1.65	1.95	1.68	8.68
1980	9.42	0.54	1.52	2.19	13.67
1985	12.68	0.68	1.44	2.94	17.74
1990	17.57	1.22	1.15	3.54	23.48
1995	22.22	1.87	1.12	4.29	29.5
1999	24.45	2.07	—	4.60	31.12

TABLE 3
N Flux on Land in China from 1949 to 1999

Year	Synthetic N Fertilizers	Excrements N from Animals and Humans	N Flux on Land
	(Tg N)	(Tg N)	(kg N km ⁻² year ⁻¹)
1949	0.006	5.62	586
1952	0.039	6.86	719
1957	0.32	8.17	884
1962	0.49	7.52	834
1965	1.33	9.00	1076
1970	2.52	10.15	1320
1975	3.40	11.33	1534
1980	9.42	12.18	2250
1985	12.68	12.96	1671
1990	17.57	14.88	3380
1995	22.22	17.91	4180
1999	24.45	19.12	4539

TABLE 4
N Flux on Land in Different Regions in China (1995)

Country and Region	Area (10 ⁴ km ²)	Population Density (individual km ⁻²)	Synthetic N (Tg N)	Excrements N (Tg N)	N Flux on Land (kg N km ⁻² year ⁻¹)
China	960	123	22.22	17.91	4187
Changjiang Valley	181	226	7.30	5.32	8188
Huanghe Valley	75	101	1.77	1.44	4293
Zhujiang Valley	45	215	1.47	1.36	7244
Eastern China ¹	103	426	8.94	5.68	14,262
Taihu Valley	3	1080	0.72	0.18	30,000
Central Western China ²	704	52	5.58	7.21	1816
Remote Western China ³	406	10	0.77	2.53	622
Tibet	122	2	0.00089	0.39	327

¹ Includes provinces of Liaoning, Hebei, Shangdong, Jiangsu, Zhejiang, Fujian, and Guangdong, and autonomous metropolitan cities of Beijing, Tianjin, and Shanghai.

² Includes provinces of Xining, Sichuang, Yunnan, Guizhou, Guangxi, Xinjiang, Qinghai, Gansu, Ningxia, Shanxi, Shannxi, and Mongolia.

³ Includes autonomous regions of Tibet, Xinjiang, and Inner Mongolia.

As shown in Table 4 with respect to major river valleys, N flux on land of the Chanjiang Valley was higher than that of the Zhujiang Valley, which was higher than that of Huanhe Valley. N flux on land of the Chanjiang Valley and Zhujiang Valley was two times higher than the national average. Along the coast, the magnitude of N flux on land of the ten provinces (metropolises) reached 14,262 kg N km⁻² year⁻¹. The Taihu Valley had the highest N flux on land (30,000 kg N km⁻² year⁻¹). The inland provinces of western China has 1816 kg N km⁻² year⁻¹ of N flux on

land, which was twofold lower than the national average. In the remote regions of western China, such as Tibet, Xinjiang, and Inner Mongolia, N flux on land was at 622 kg N km⁻² year⁻¹, which was eight times lower than the national average (Table 4).

N flux on land in China far exceeded that of other countries around the world. Howarth et al.[17] reported that the maximal N flux on land was found in the watersheds around the North Sea at 1450 kg N km⁻² year⁻¹. This value, however, was lower than the national average of China and even far lower than that of the

provinces (metropolises) of eastern China along the coast (Table 4). Even the lowest N flux on land ($327 \text{ kg N km}^{-2} \text{ year}^{-1}$) in China found in Tibet far exceeded the reported $76 \text{ kg N km}^{-2} \text{ year}^{-1}$ in Canada [17]. The markedly high N flux on land in China has already greatly influenced the environment of the coast and water bodies.

Atmospheric N Deposition in China

Atmospheric deposition N, which derived from NH_x and NO_x in precipitation and dust has profoundly affected the terrestrial and oceanic ecosystems. In our current study, due to the lack of information on dry N deposition, only the wet atmospheric N deposition was calculated in Table 5. The amount of wet N deposition was estimated based on the data obtained in the early 1990s under the assumption that the current amount of wet N deposition was underestimated in Table 5 due to increases of anthropogenic reactive N input into watersheds and excrements N of animals and of humans in the late 1990s (Table 2, Table 3).

The ratio of NO_3 to NH_4 of wet N deposition in China and its major river valleys was significantly higher than that of other countries in the world [18,19,20]. In China, the ratio of NO_3 to NH_4 was one third for both the Changjiang and Zhujiang Valleys, one fourth for the Huanghe Valley, and one sixth for the Taihu Valley, demonstrating a high concentration of NH_4 in the precipitation. The large amount of wet N deposition in China could be attributable to the use of a specific type of synthetic N fertilizer made up of urea and ammonium bicarbonate. It accounts for 97.59% of the synthetic N fertilizer consumption, half of which is ammonium bicarbonate when volatilized, giving rise to NH_3 . High levels of NH_3 volatilization in China were also caused by the ill management of animal waste and excrements due to the lack of the well-equipped establishments. In the Huanghe Valley, the high ratio of NO_3 to NH_4 was a result of NH_3 volatilization of synthetic N fertilizers entering the farmland caused by calcareous soil with a high pH. In the Taihu Valley, the ratio of NO_3 to NH_4 was as low as one sixth. This might be related to the high N flux on land ($30,000 \text{ kg N km}^{-2} \text{ year}^{-1}$) in this region (Table 4).

N_2O and NH_3 Emitted From Farmland in China the Past 50 Years

As an important greenhouse gas, 70 to 90% of N_2O that escaped into the atmosphere originated from the soil [21]. The application of chemical N fertilizers was the major cause of N_2O generation in agricultural land [12,22]. As a major agriculture producer, China stands first on the list in the consumption of synthetic N fertilizers.

In this study, direct N_2O emission from agricultural fields and contributions of different N sources to N_2O emission at different time points between 1949 and 1999 were estimated using the IPCC Phase II Methodology (1996) (Table 6).

As shown in Table 6, the direct N_2O emission at $373 \text{ Gg N}_2\text{O-N}$ from farmland in 1999 was 15 times higher than in 1949. The contribution of different N sources to N_2O emission was also tabulated in Table 6. In 1999, animal waste and human excrements as fertilizers, synthetic N fertilizers, biological N fixation, and crop residue accounted for 13, 74, 7, and 6% of N_2O emission respectively compared with 0.3, 51, 40, and 4% of each in 1949. Besides, the cultivated histosols accounted for 4% of N_2O emission from farmland in China in 1949. In 1949, animal wastes, human excrements, and biological N fixation were the major sources of N_2O emission, making up over 91% of the total. In contrast, synthetic N fertilizers had very little effect on N_2O emission. However, the consumption of synthetic N fertilizers has increased sharply since 1980, and the contribution of synthetic N fertilizers to N_2O emission from farmland rose to 67% of the total. In addition, the N_2O emission from arable land and paddy fields in China was calculated based on data observed from agricultural fields (Table 7).

Table 7 demonstrated that 310 Gg N , which accounted for 78% of the total N_2O emission, was emitted from arable land. The rest (88 Gg N , which accounted for 22%) originated from paddy fields, 35 Gg N (9% of the total emission) of which was emitted from paddy fields during the rice-growing season and 53 Gg N (accounting for 13% of the total) of which was emitted during the arable-land cropping season. The relatively high N_2O emission from paddy fields in China was related to the

TABLE 5
Atmospheric Wet Deposition N in Major Regions of China

Country and Region	Area (10^4 km^2)	Precipitation ($10^3 \text{ mm year}^{-1}$)	Wet N Deposition			NO_3/NH_4
			From NH_4	From NO_x (Tg N)	Total	
China	960	0.63	8.28	2.68	11.36	1/3
Changjiang Valley	181	1.05	2.79	0.96	3.75	1/3
Huanghe Valley	75	0.49	0.52	0.12	0.64	1/4
Zhujiang Valley	45	1.44	0.96	0.33	1.29	1/3
Taihu Valley	3	1.1	0.0364	0.0062	0.043	1/6

TABLE 6
Direct N₂O Emission from Agricultural Fields in
China Estimated by IPCC Phase II Methodology (1949 to 1999)

Year	Direct Soil Emissions (Gg N year ⁻¹)					Total
	Synthetic Fertilizer	Animal Waste	Biological N Fixation	Group Residue	Cultivated Histosols	
1949	0.07	13.4	10.4	1.1	0.95	26
1954	3.6	18.1	16.8	5.3	0.95	48
1960	5.5	17.6	15.3	4.8	0.95	44
1965	15.0	21.4	19.3	6.4	0.95	63
1970	28.2	24.6	28.5	7.5	0.95	90
1975	38.4	27.5	30.1	9.2	0.95	106
1980	106	28.5	12.5	11.2	0.95	159
1985	142	31.1	17.4	14.1	0.95	253
1990	196	35.1	17.5	16.9	0.95	266
1995	250	44.0	23.2	17.8	0.95	336
1999	275	47.8	25.8	23.2	0.95	373

TABLE 7
N₂O Emission from Cropland in China (Gg N year⁻¹)

Total Emission	Arable land		Paddy field		N ₂ O Emission during Rice Growing Season		N ₂ O Emission from Rice Field after Rice Harvest	
	Emission	% Total	Emission	% Total	Emission	% Total from cropland	Emission	% Total from cropland
398	310	78	88	22	35	9	54	13

Data from Xing[12].

paddy fields' unique systems of water management and cropping[12].

NH₃ volatilization is not only an important pathway of N loss in agriculture to the atmosphere in the form of NH₃, but it also affects the oxidation of CH₄, a key greenhouse gas in the atmosphere[23]. Furthermore, NH₃ is a major component of atmospheric dry/wet N deposition. Once deposited on terrestrial ecosystems, NH₃ functions as the second source of N₂O despite of the enhanced nutrients on farmlands. Excessively deposited NH₃ in water ecosystems, however, will increase N load, which in turn will lead to adverse consequences. In the current study, variations of NH₃ volatilization in terrestrial parts of China over the past 50 years were estimated (Table 8).

As shown in Table 8, the amount of NH₃ volatilization has increased steadily in the past 50 years. Although the consumption of synthetic N fertilizers increased sharply year by year, the contribution of excrements of animals and of humans to terrestrial NH₃ volatilization was still greater than that of synthetic N fertilizers in China. In 1949, NH₃ volatilization derived from excrements N of animals and of humans accounted for almost

100% of the total NH₃ volatilized. Despite the significant increase in consumption of synthetic N fertilizers in 1999 (consumption has gone up to 24.44 Tg N), only 40% of the total NH₃ volatilization originated from synthetic N fertilizers. About 60% of the total arose from animal and human excrements. Therefore, NH₃ volatilization generated from excrements N of animals and of humans has had significant effects on atmospheric environment, terrestrial ecosystems, and aquatic ecosystems.

Transportation of N from Land to Water Bodies in China

Some observations on N transportation from land to water bodies were reported. Based on studies of the Changjiang, Zhujiang, and Huanghe regions from 1980 to 1989, Duan et al.[24] calculated the amount of N transportation from these three rivers to the Pacific Ocean to be 0.78, 0.06, and 0.15 Tg, respectively. However, the estimation of Xing and Zhu[3] was 3.79 Tg for Changjiang, 0.84 Tg for Zhujiang, and 0.84 Tg for Huanghe.

TABLE 8
NH₃ Volatilization in the
Terrestrial Part of China over the Past 50 Years

Year	From Synthetic N Fertilizers	From Excrements N of Animals and Humans	Total
	(Tg)		
1949	0.0007	1.12	1.12
1952	0.0043	2.36	1.36
1957	0.004	2.63	1.63
1962	0.054	2.50	1.60
1965	0.146	2.80	1.95
1970	0.227	2.03	2.31
1975	0.374	2.27	2.64
1980	1.04	2.44	3.47
1985	1.39	2.59	3.99
1990	1.93	2.98	4.96
1995	1.44	3.58	6.04
1999	2.69	3.82	6.51

Considerable discrepancies in estimation of N transportation from land to water bodies calls for further investigation. Based on limited observation data, Zhu[25] recently estimated that the amount of N loss via farmland runoff and leaching were 1.24 and 0.5 Tg, respectively, which accounted for 5 and 2%, respectively, of applied synthetic N fertilizers in farmland.

N leaching in the farmland is a complex process. As discussed above, natural and social conditions differ greatly among different regions of China. Thus regions included in this study were categorized into three groups: paddy fields in southern China, the North China Plain, and the Loess Plateau to investigate N leaching and accumulation of N in the soil of farmland in China.

Nitrogen Leaching in Rice Paddy Fields of Southern China[26,27,28]

Rice paddy fields cover one fourth of the total cultivated areas in China and are largely distributed in the south of the Changjiang River, which has an annual precipitation of 1000 to 2000 mm and an application rate of ha⁻¹ fertilizers at 400 to 600 kg N. In these areas, the paddy fields are cultivated under a paddy-arable land rotation system with the alternation of rice crops in the summer and other crops (such as wheat and oil rapes) in the winter.

Based on the data obtained, as shown in Table 9, the ratio of leaching NO₃⁻ to the application rate of synthetic N fertilizers was not high regardless of the geographic locations of rice paddy fields (the north vs. the south of China).

It is clear that regardless of rice or wheat growing season, there was very little N leaching from applied N fertilizers in the farmland (ranging from 0.27 to 3.01%) in rice growing season. However, it was closely related to the amount of N fertilizers applied. Comparing two application rates showed that the larger

the amount of N fertilizers applied, the higher the level of leaching N. The leaching N was slightly higher in wheat-growing season than in rice-growing season.

As reported by Lu et al.[29], estimation of leaching N derived from synthetic N fertilizers and endogenous soil N in rice paddy fields of southern China ranged from 5 to 10 kg N ha⁻¹ year⁻¹. This value is fairly low despite of the application of synthetic N fertilizers ranging between 400 and 500 kg N year⁻¹ ha⁻¹ to accommodate the double- or triple-cropping systems that dominate agricultural production in these areas. These results indicate that the level of leaching N derived from N fertilizers usage in rice paddy fields was low in southern China.

The low level of leaching N from synthetic N fertilizers in rice paddy fields could be attributable to two reasons: first, little NO₃⁻ was generated during rice growing season due to the presence of flooding water above the ploughed soil layer; second, denitrification existed in the saturated underground soil layer of paddy fields in both rice and wheat growing season[4], suggesting that less NO₃⁻ existed in the saturated underground soil layer.

In contrast, the amount of leaching N in the hilly arable land fields was much higher in southern China. Lu et al.[29] reported that the leaching N in the upland of red soil consisted of 15 to 27% of the total application of N fertilizers under an annual precipitation of 2182 mm. Since there is very limited information on N leaching in southern China, the amount of leaching in this region is not accurately known.

Leaching N in Arable Land of the North China Plain

The North China Plain, located between 30 to 40° latitude N and 114 to 121° longitude E, is also known as the Huanghuaihai Plain. As one of the three major plains in China, the North China Plain

TABLE 9
N Leaching in Rice Paddy Fields

Observation Sites	Application N (kg N ha ⁻¹ year ⁻¹)	% Leaching NO ₃ ⁻ to Application N		Observation Methods	Data Sources
		Rice Growing Season	Wheat Growing Season		
Jiannin	600 ¹	1.8	3.4	Lysimeter	26
Changzhou	254	0.56	—	Lysimeter	27
	388	3.01	—		
Shenyang	150	0.27	—	Lysimeter	28
	250	0.46	—		

¹ Indicates the application rate of N fertilizers during rice-wheat growing seasons.

covers an area of 0.3 million km² and is the alluvion formed by the Huang, Huai, and Hai Rivers. Most areas of this plain have semi-arid and semi-humid climates with an average annual rainfall of 640 mm. Two-crop planting once a year or three-crop planting every other year is a popular practice for this region, the biggest region for the cultivation of arable land crops. There have been very few results obtained on leaching N (Table 10).

Results summarized in Table 10 indicate that the level of leaching N in the arable land of the North China Plain was not high. Despite the better correlation of leaching N with the application rate of synthetic N fertilizers, great spatial variation still existed in the North China Plain. The ratio of leaching N to the applied N in farmland varied 2.0 to 17.2%[30,31,32]. The monsoon climate in the North China Plain could account for the low rate of leaching N. About 60 to 70% of rainfall could be accounted for in June, July, and August, the full growing stage of the crops. In this stage, crops consume much more NO₃⁻ in soil than any other stages. Normally, crops planted in winter are subject to arid conditions during the growing period. The downward transport of NO₃⁻ could only be observed in irrigation farmlands in the spring.

Leaching and Accumulation of NO₃⁻ in Farmland of the Loess Plateau in China

Between 34 to 40° latitude N and 102 to 114° longitude E locates the loess layer, which is 50 to 150 m in depth. With an average rainfall of 450 mm largely in July, August, and September, most areas are suitable only for single-crop planting once a year despite the fact that it is the biggest area for arable land crop production. Due to the little precipitation and the thickness of loess soil, the water table of underground water is 50 to 60 m lower than the surface soil, and in some areas, it can be 100 to 200 m lower. Although relatively much more NO₃⁻ leaches from the ploughed layer into 20- to 60-cm-deep soil[33] or into 60- to 90-cm-deep soil[34], NO₃⁻ in the surface soil of the Loess Plateau can only translocate downwards 1 to 1.5 m in depth during the fallow summer period[35].

Lu et al.[36] reported that the accumulation of NO₃⁻ was within 0 to 4 m of the soil layer with different applications of N fertilizers and land usage. The accumulated NO₃⁻ within 4 m reached 3414 kg N ha⁻¹ in a 8-year-old apple garden with the application rate of 900 kg N ha⁻¹ year⁻¹.

TABLE 10
Leaching in Arable Land of the North China Plain

Observation Site	Application N (kg N ha ⁻¹ year ⁻¹)	Leaching N to N Applied (%)	Observation Methods	Data Sources
Lanfang	173	3.6	Lysimeter	30
Beijing	150	0.9	Lysimeter	31
	225	2.0		
Beijing ¹	75	1.8	Lysimeter	32
	300	17.2		

¹ The averaged data from 1986 to 1992.

The accumulation of N in the soil layer under the ploughed layer was not only observed in farmlands of the Loess Plateau but also in arable land of the North China Plain. In the northern part of the Huanghuaihai Valley in the Beijing region, NO_3^- accumulation happened mostly in the arable land soil above 0.4 m [37] with very little NO_3^- moved into the soil layer under 1.4 m [38]. Chen et al. [39] reported that NO_3^- in farmland could leach 1.3 m or deeper into the soil layer during corn growing season in the summer. In contrast, in wheat growing seasons, the accumulation of N in the soil layer fluctuated between 0.4 and 0.6 m in depth. In the present, the excessive exploitation of underground water has caused the water table to fall in this region. For instance, as reported by Wu [40], the table of underground water in the Beijing region has declined to 18 to 40 m at a rate of 1 to 2 m year⁻¹. It was hard for the downward NO_3^- from ploughed soil to enter the underground water despite its potential endangerment to the underground water.

N Pollution of Water Bodies in Developed Regions of China

N pollution of water bodies, one of the most serious environmental issues, has already raised alarming warnings in many regions of China, particularly the developed regions. As shown in Table 10, in the Taihu Valley, a developed region in the low reaches of the Changjiang River, N pollution of water bodies has deteriorated gradually.

As indicated in Table 11, N pollution in the river was worse than that of the lake. Inorganic N and PO_4^{3-} exceeded their critical concentrations for eutrophication of lake water, particularly the N concentration. The shallow wells of 5 m or so for domestic usage in the rural area have an average concentration of $7.98 \pm 9.65 \text{ mg NO}_3\text{-N l}^{-1}$. Of the wells under the investigation, 28% had NO_3^- concentrations above the critical value of $10 \text{ mg NO}_3\text{-N l}^{-1}$. The potential sources of N pollution in the river and the lake as well as in wells of the Taihu Valley were reported by Xing et al. [4]. N pollutants in rivers and lakes were mainly from the domestic sewage and excrements of the domesticated animal and human populations while N pollutants in wells were from nitrogen leaching into farmlands [4]. However, the potential effect of dry/wet N deposition on the turnover of N in surface water (river and lake) could not be excluded. The amount of wet N deposition reached $0.043 \text{ Tg N km}^{-2} \text{ year}^{-1}$ (Table 5). The area of the

Taihu Lake and Yangcheng Lake is over 2950 km^2 . If calculated on the basis of the two lakes' maximum volume of 8 billion m^3 , the wet N deposition could give a 0.46 mg l^{-1} increase of N concentration every year.

CONCLUSION

Human activities had trivial effects on N cycling in China 50 years ago. The input of N in watersheds of China was mainly from the excrements of the animal and human populations, N fixation by legume crops, and nonsymbiotic N in farmland. Since the 1980s, however, the consumption of synthetic N fertilizers has increased drastically from 0.006 Tg N in 1949 to 9.42 Tg N in 1980, and again to 24.45 Tg N in 1999 whereas the excrements of animals and humans have only increased from 5.62 Tg N in 1949 to 19.12 Tg N in 1999. N flux on land ranged from $586 \text{ kg N km}^2 \text{ year}^{-1}$ in 1949 to $4539 \text{ kg N km}^2 \text{ year}^{-1}$ in 1999 in China, which was significantly higher than that of any other country. Great attention has been given to the N pollution of water bodies in China, the red tide in the estuary, and the eutrophication in lakes exacerbated year by year. Excessive inputs of N in water bodies might be responsible for it. The sources of nitrogen pollutants are mainly from the domestic sewage in cities and the discharge of the excrements of animals and humans into the water bodies. The sources could be also runoffs from farmland and atmospheric dry/wet N deposition.

N leaching in farmland varied widely among different regions due to the variations of climate, land use, and cropping systems. The amount of N leaching in farmland of the North China Plain and the northwestern Loess Plateau was not high. While it was even lower in the rice paddy field, it is relatively higher in the hilly upland in the humid climate zone of southern China. The movement of N from ploughed layer to underlayer soil was observed despite the limited depth of translocation.

The water table of underground water of the Loess Plateau is usually 50 m deep due to the extraordinarily thick loess soil, arid climate, and plateau topography. As a result of increased industrial and agricultural demand for water usage, excessive exploitation of underground water in North China Plain caused a more than 50-m reduction of the underground water table. Considering the continuous decline of the underground water table in the North China Plain and the Loess Plateau, the gradually accumulated N in the soil under the ploughed layer posed a

TABLE 11
N Concentration in the River, Lake, and Well Water of the Taihu Valley (2000)

Water Body	NO_3^-	NH_4^+	Total N	PO_4^{3-}
	(mg N l ⁻¹)			(mg P l ⁻¹)
River	1.36 ± 0.68 (n = 23)	5.69 ± 4.26 (n = 23)	7.99 ± 4.44 (n = 23)	0.20 ± 0.24 (n = 13)
Lake ¹	1.27 ± 0.98 (n = 7)	0.33 ± 0.43 (n = 7)	1.88 ± 1.46 (n = 7)	0.022 ± 0.085 (n = 7)
Well	7.89 ± 9.65 (n = 40)	<0.2		

¹ The Taihu Lake and the Yangcheng Lake.

potential threaten to the underground water even though it is unlikely that NO_3^- may leach into the underground water bodies within a short period of time. Although there are some reports on NO_3^- pollution of underground water in some regions of North China, nitrogen pollutants affect more the surface water than the underground water.

Of the total rice paddy fields in China, about 86% are cultivated under a paddy-arable land rotation system. During the rice-growing period, at least one cycle of dry-and-wet alternation is practiced in rice paddy fields. The unique cropping systems have made paddy fields an important source of N_2O , which consists of 22% of the total N emission from agricultural fields in China. Great uncertainties yet reside in what and how atmospheric dry/wet N deposition affects the terrestrial ecosystems such as forest, grassland, and natural wetlands, and further studies should be carried out in the near future.

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