Analysis of Anthropogenic Nitrogen and Its Influencing Factors in Beijing

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Abstract: Human activities have changed the global nitrogen cycle and are continuing to do so at an alarming rate. Cities are particularly important nitrogen sinks due to the concentration of human activities, and have attracted widespread attention. However, researchers disagree about the sink size and the underlying socioeconomic factors. Taking Beijing as an example, we developed an anthropogenic nitrogen index to characterize the sink size and the effects of socioeconomic factors, then we used empirical coefficients for the nitrogen content of materials to calculate the total anthropogenic nitrogen consumption and analyzed its structural characteristics. We used the logarithmic mean divisia index to construct a factor decomposition model and analyze the factors affecting anthropogenic nitrogen consumption and their contribution and direction (promotion or inhibition). Beijing's anthropogenic nitrogen consumption increased from 1995 to 2010 in response to increasing consumption of energy, food, and fertilizer nitrogen. Energy nitrogen accounted for the largest proportion of the total

(≥33%) and increased greatly. The proportion of food nitrogen increased from 10% to 21% during the study period. Subsequent decreases in anthropogenic nitrogen mainly resulted from decreased fertilizer nitrogen consumption (to 20% of the total consumption) from 2010 to 2015. Of the influencing factors, the inhibitory effect of material intensity on Beijing's anthropogenic nitrogen consumption increased from 22% to 37% during the study period; the promoting effect of per capita GDP gradually weakened, but its contribution remained >30% of the total. By analyzing the dynamics of Beijing’s urban anthropogenic nitrogen consumption, we identified the main socioeconomic drivers, thereby providing scientific support for exploring nitrogen consumption patterns during different urban development stages and for the activities required to regulate nitrogen consumption.

Key words: anthropogenic nitrogen, urban metabolism, consumption, influencing factors, LMDI method, Beijing

1. Introduction

During the 145 years from 1860 to 2005, the world's rate of anthropogenic nitrogen production increased by more than 12 times (Galloway et al., 2008), and human reactive nitrogen sources are ~ 5-fold greater than natural sources in 2002 (Galloway et al., 2015). Human activities significantly affected the global nitrogen cycle. Unfortunately, this high nitrogen consumption has caused many ecological and environmental problems (Billen et al., 2013, Gao et al., 2019). For example, global NH_3 and NO_x emission caused by food and energy production increased nearly threefold between 1860 and 1990 (Galloway et al., 2004), adversely affecting human health and regional sustainability (Luo et al., 2018). Due to the high concentration of people and socioeconomic activities that occurs in cities, these problems become particularly prominent at the scale of cities, and cities have become global hotspots of concern (Gu et al., 2009). Urban areas account for 50% of all waste, generate 60 to 80% of all greenhouse gas emissions, and consume 75% of natural resources, yet occupy only 3% of the Earth's surface (UN-DEAS, 2015).

Beijing, China, is a global megacity whose high nitrogen inputs and nitrogen pollution cannot be ignored. In 2015, Beijing's urban per capita food expenditure (7584 yuan/person) was 1.6 times the national average (4814 yuan/person) (BMBS, 2016; NBSC, 2016d). Beijing's urban per capita energy consumption (3.2 tonnes coal equivalent [tce]/person) was 1.1 times the national average (2.9 tce/person) (NBSC, 2016a). Increasing consumption of food and energy due to increasing urbanization and socioeconomic development greatly increased nitrogen inputs, leading to serious nitrogen pollution. The NO_x emissions from Beijing residents (19 143.0 t) was 3.9 times the national average urban emission (4931.1 t) and the emission of ammonia and its discharge into water by residents of Beijing (11 564.0 t) was 1.3 times the national average urban emission (9172.6 t) (NBS and MEP, 2016). To control Beijing's nitrogen pollution, we need to calculate the nitrogen consumption from the various sources, clarify the structural characteristics of this consumption, and identify the main factors that influence nitrogen consumption in Beijing. This knowledge will let managers propose targeted policy recommendations to improve urban metabolic flows that lead to healthier conditions for the citizens and the global nitrogen cycle.

Researchers have proposed a range of indicators for characterizing nitrogen consumption to meet different research purposes. Agricultural researchers have proposed indicators for nitrogen input in agricultural activities. For example, Jordan & Weller (1996) proposed net anthropogenic nitrogen input. Billen et al. (2007) proposed the concept of artificial autotrophic nitrogen and heterotrophic nitrogen, which reflect the nutrient inputs in the early stage of agricultural production, local agricultural production activities, and the population's geographical distribution (Zhang et al., 2016b). Other researchers have proposed indicators for characterizing the nitrogen inputs of the socioeconomic system. For example, Deng et al. (2007) and Ma et al. (2010) used a similar partitioning method to classify regional nitrogen inputs into reactive nitrogen and recirculating nitrogen. However, Ma et al. (2010) called reactive nitrogen "new nitrogen" and did not incorporate atmospheric deposition of nitrogen into the pool of circulating nitrogen.

As the scale and intensity of human activities has increased, anthropogenic nitrogen indexes have been developed to quantify these flows. For example, in a century-scale analysis of the creation and fate of reactive nitrogen in China, Cui et al. (2013) accounted for biological nitrogen fixation, industrial nitrogen fixation, and fossil fuel combustion as anthropogenic nitrogen. The accounting system of Gu et al. (2012)

was more detailed; they noted that an anthropogenic nitrogen index should include fossil fuel nitrogen, fertilizer nitrogen, industrial nitrogen (e.g., in nylon, plastics, paints, and dyes), nitrogen imports in food and livestock feed, and biological nitrogen fixation, as these sources are closely related to human activities. They also studied the impact of the urbanization process on the forms of nitrogen in Shanghai, China, and dynamic mechanisms responsible for changes in these forms. The anthropogenic nitrogen index proposed by Gu et al. was relatively comprehensive, but they did not separate biological nitrogen fixation (natural nitrogen fixation) from agricultural nitrogen fixation. In contrast with Gu et al.’s accounting system, Gao et al. (2014 a) did not consider fossil fuels and industrial nitrogen in their net anthropogenic nitrogen index, but included atmospheric nitrogen deposition and applied it to the calculation of nitrogen flows for 358 regional-level municipal administrative units in mainland China. The same accounting system was also applied to the net anthropogenic nitrogen input in a study in the Victoria Basin in East Africa (Zhou et al. 2014) and the Huaihe River Basin in China (Zhang et al. 2016a). In addition, unlike previous studies, Luo et al. (2018) considered nitrogen in industrial use, human consumption, and agriculture, and the nitrogen recovered by the waste management system in coupled human–environment nitrogen flows in China.

The dynamic changes in anthropogenic nitrogen consumption indicators are driven by changes in socioeconomic factors. Two main methods for analyzing the factors that influence nitrogen consumption have been widely used: correlation analysis and factor analysis. Yu et al. (2012) used Pearson’s correlation coefficient to analyze the effects of factors such as per capita disposable income, Engel's coefficient, a food price index, the university-level population, and the average household population on food nitrogen consumption in Xiamen, China. Similarly, Gao et al. (2018) used correlation analysis to study the effects of population growth, dietary changes, and urban–rural migration on China's food nitrogen consumption. Correlation analysis provides a flexible approach, but cannot comprehensively consider and quantify the relative contribution of each factor. Factor analysis can accomplish both goals, and among the available methods, structural decomposition analysis and index decomposition analysis are the most common methods. Structural decomposition analysis has certain limitations to its application because the data is based on input–output tables, and this data is only available for a limited period in most regions, and the decomposition results have residuals. The logarithmic mean divisia index (LMDI) method, which is a form of index decomposition analysis, has the advantages of using available data, performing a full decomposition of that data, having no residuals, being easy to use, and being consistent with both multiplicative and additive decomposition (Gu, 2011). Thus, it offers many advantages over simple correlation analysis and other factor decomposition methods (Ang, 2004).

In the context of nitrogen, the LMDI method has mainly been applied to nitrogen pollutant emission, with the goal of decomposing the factors that drive nitrogen emission in terms of their structure, scale, efficiency, and intensity, while also accounting for social and technological improvements. The structural effects used in previous studies always included factors related to the economic and energy structure of the system being studied (Wang, 2017) and its industrial structure (Lei et al., 2012). The scale effect included factors such as the economic scale (Jia et al., 2017), population (Gao et al., 2014b), and industrial scale (Li et al., 2012). The use of other effects has been relatively rare, and mainly included factors such as energy efficiency (Ding et al., 2017), energy intensity (Wang, 2017), and technological improvement (Pang et al., 2013). Since emission results from consumption, analyzing the different factors that influence emission can provide a reference for research on nitrogen consumption. Liu et al. (2014) used the LMDI method to study the contribution rates and the promotion or inhibition effects of factors such as population, economic scale, nitrogen consumption intensity, and food efficiency on regional food nitrogen consumption.

Previous studies using the LMDI method to study the factors that influence nitrogen consumption began with the discharge end to explore the causes of nitrogen pollution. However, emissions are usually derived from consumption. From the perspective of consumption, researchers most often try to predict future nitrogen problems, and their predictions can be used to guide efforts to solve the problem of excessive resource consumption and thus reduce nitrogen pollution. However, few scholars have combined the consumption of all types of urban anthropogenic nitrogen with the LMDI method to study the influencing factors. Liu et al. (2014) used the LMDI method to study the contribution ratio and direction of factors such as population, economic scale, nitrogen consumption intensity and food efficiency to regional food nitrogen consumption, but the type of nitrogen studied is too singular. Table S1 summarizes the history of previous research on nitrogen flows.

To provide some of the missing knowledge, we designed the present study to start with consumption and develop an anthropogenic nitrogen index that characterizes the most important nitrogen sinks affected by socioeconomic factors. We studied the changes of total anthropogenic nitrogen consumption and its structural characteristics in Beijing from 1995 to 2015. We used the LMDI method to construct a factor decomposition model that included six factors: 1) the nitrogen content of the material, 2) the material intensity (i.e., the material consumption per unit of the output value), 3) the industrial structure, 4) the per capita GDP, 5) the material consumption structure, and 6) the population. These factors represent the intensive and extensive aspects of Beijing nitrogen consumption in the context of current structural considerations. We chose these factors based on our knowledge of Beijing’s current situation, the problems it is facing as a result of urban development, and the availability of reliable and comparable data for the whole study period. We then examined this data to identify the main factors that promoted or inhibited Beijing’s consumption of reactive nitrogen. The results provide scientific support for developing policies to control nitrogen consumption, with the goal of promoting healthy and stable development of Beijing’s nitrogen system.

2. Methodology

In this study, we focused on Beijing's nitrogen consumption and changes in its structural characteristics. We also focused on the main factors that influence Beijing's nitrogen consumption and changes in their relative importance over time. We used empirical coefficients for the nitrogen content of materials and statistical analysis to calculate the inputs of anthropogenic nitrogen to Beijing’s urban system from 1995 to 2015 to reflect the changes of total nitrogen consumption and their structural characteristics. We used the LMDI method to construct a factor decomposition model, and used the model to analyze the contribution of socioeconomic factors to anthropogenic nitrogen consumption, and the strength of their promotion or inhibition of the N flows (Fig. 1).

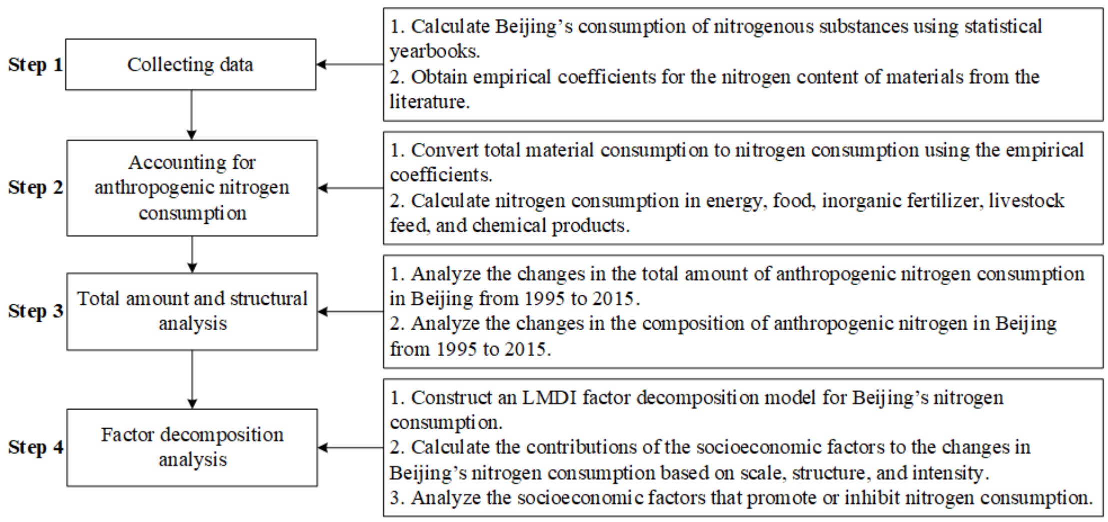

Fig. 1. Overview of the steps in the research.

2.1 Accounting for anthropogenic nitrogen consumption

The anthropogenic nitrogen index (N_a) is composed of the amount of energy nitrogen (N_{energy}, primarily from combustion of fossil fuels), food nitrogen (N_{food}), fertilizer nitrogen ($N_{fertilizer}$), livestock feed nitrogen (N_{feed}), and inorganic nitrogen ($N_{inorganic}$):

$$N_a = N_{energy} + N_{food} + N_{fertilizer} + N_{feed} + N_{inorganic} \quad (1)$$

Based on this nitrogen accounting, we analyzed Beijing's total input of anthropogenic nitrogen and the dynamic changes of the five anthropogenic nitrogen components from 1995 to 2015. We calculated the quantity of nitrogen in each kind of nitrogen input by multiplying the consumption data for materials in each category by an empirical coefficient that defined the nitrogen content of the materials (Table 1). Table S2 provides these coefficients or their sources for all the materials other than fuels and food that we evaluated. We obtained most of our data from government statistical yearbooks, and we obtained the nitrogen content of the materials from previous research results. To more accurately and comprehensively calculate the amount of nitrogen consumed by energy combustion, we used the NO_x emission data and Asian fuel NO_x emission factors that were closest to Beijing's emission levels (Kato and Akimoto, 1992). Table S3 provides the emission factor values we used for different types of fuel. Table S4 provides these factors for food. The nitrogen content of fertilizers was the average nitrogen content reported for Chinese compound fertilizers (Ti et al., 2012). Because most nitrogen fixation by Chinese crops results from fertilizer nitrogen (Gao et al., 2014a), and because nitrogen-fixing leguminous crops represent less than 5% of Beijing’s total crop area (BMBS and NBS, 1996-2016), we did not include biological nitrogen fixation in our calculations.

Table 1 Accounting formulas and data source used to quantify anthropogenic nitrogen

Categories		Calculation formula	Data description	Data Sources
$N_{fertilizer}$		$D_1 \times P_1$	D_1: Fertilizer consumption	NBSC, 2016d
			P_1: Fertilizer nitrogen content	Table S2
N_{feed}	N_{pet}	$D_4 \times D_5 \times 365 \times P_4$	D_4: Number of pets per person	EBCAIY, 2016
			D_5: Beijing's population	BMBS and NBS, 1996-2016
			P_4: Feed nitrogen consumption / pet / day	Table S2
	$N_{livestock}$ & poultry	$D_6 \times P_5 \times P_6$	D_6: Number of livestock and poultry	NBSC, 2016c, EBCAIY, 2016; MAC,2016
			P_5: Feed nitrogen consumption of livestock and poultry / animal / day	Table S2
			P_6: The number of days of breeding of various types of livestock and poultry	Table S2
	$N_{fisheries}$	$D_7 \times P_7$	D_7: Aquatic product production	MAC, 2016
			P_7: Empirical coefficient for N content	Table S2
N_{energy}		$\sum D_{sf} \times P_{sf}$	D_{sf}: consumption of fuel type *f* in sector *s*	NBSC, 2016a; NBSC, 2016b
			P_{sf}: NOx emission factors of fuel type *f* in sector *s*	Table S3
N_{food}		$\sum D_m \times P_m$	D_m: consumption of food type *m*	BMBS and NBS, 1996-2016, NBSC, 2016c, EBCAIY, 2016
			P_m: nitrogen content of food type *m*	Table S4
$N_{inorganic}$		$D_5 \times P_8$	D_5: Beijing's population	BMBS and NBS, 1996-2016
			P_8: industrial nitrogen flux per person	Table S2

Sectors (*s*) include Household, Industry, Services, Construction, Transportation, and Other. Energy types (*f*) include coal, coke, crude oil, gasoline, kerosene, diesel, residual oil, liquefied petroleum gas, natural gas, gasworks gas, and refinery gas. Food types (*m*) include cereals, beans, vegetables, fruits, pork, beef, milk, mutton, eggs, and aquaculture products.

2.2 Constructing the nitrogen factor decomposition model

We used the LMDI method to construct a complete decomposition model for the factors responsible for the changes of anthropogenic nitrogen consumption. As a global megacity, Beijing has a high concentration of socioeconomic activities and a large population. The per capita GDP and the population are therefore the factors that we need to consider to account for the intensity of these activities. In addition, Beijing is in a critical period of industrial transformation (e.g., closing industries with high energy consumption or moving them to other parts of the country) and upgrading industries through technological innovation; thus, the industrial structure must also be considered. The city's high-intensity socioeconomic activities and deep industrial transformation change the pressure created by resource consumption and its environmental impacts. Therefore, reduced consumption of materials has become an urgent task, and material intensity (the consumption of a material per unit output) has become a factor that must be considered. In addition, the variety of urban industries, the complex dietary structure of residents, and differences in consumption levels all affect the consumption structure of materials, so we focused on the material consumption structure. Based on this review, we identified the effects of six factors: 1) the nitrogen content of each material, 2) the material consumption intensity, 3) material consumption structure, 4) industrial structure, 5) per capita GDP, and 6) population on the changes of Beijing's anthropogenic nitrogen.

We also examined the direction of the effect to determine whether these factors promoted or inhibited nitrogen consumption (C_{N}). The calculation formula is as follows:

$$C_{\mathrm{N}} = \Sigma_{ij} N_{ij} = (\Sigma_i \frac{N_i}{M_i}) \times \frac{M_i}{M_j} \times \frac{M_j}{G_j} \times \frac{G_j}{G} \times \frac{G}{P} \times P \qquad (2)$$

Where N_{ij} represents the amount of N in the i-th material from the j-th industry;

N_i represents the amount of N in the i-th material; M_i represents the consumption of the i-th material; M_j is the material consumption by the j-th industry; G_j represents the output by the j-th industry; G represents the regional GDP (the real GDP, inflation-adjusted values); and P represents the population. This equation can be further expressed as follows:

$$C_N = \Sigma_{ij} N_{ij} = \Sigma_{ij} (F_i \times MS_i \times MI_j \times IS_j \times R \times P) \quad (3)$$

where F_i is the nitrogen content of the material, and most of the changes in this parameter are affected by changes in the composition of each material; MS_i is the material consumption structure, which represents the proportion of total consumption for the i-th material in the j-th industry in Beijing; MI_j is the material intensity, which represents the material consumption per unit of the output value of the j-th industry; IS_j is the industrial structure, which represents the ratio of the output value of the j-th industry to the total output value; R is the per capita GDP (the real GDP, inflation-adjusted values); and P is the population.

The change in anthropogenic nitrogen consumption from the base year (time = 0) to the target year (time = T) can be expressed as:

$$\Delta N_{tot} = N_T - N_0 = \Delta N_F + \Delta N_{MS} + \Delta N_{MI} + \Delta N_{IS} + \Delta N_R + \Delta N_P \quad (4)$$

Where ΔN_{tot} represents the change in total anthropogenic nitrogen consumption from year 0 to year T; N_T represents the anthropogenic nitrogen consumption in year T; N_0 represents the anthropogenic nitrogen consumption in year 0; and ΔN_F, ΔN_{MS}, ΔN_{MI}, ΔN_{IS}, ΔN_R, and ΔN_P represent the changes in anthropogenic nitrogen consumption caused by changes in the six factors listed above (nitrogen content of the material, material consumption structure, material intensity, industrial structure, per capita GDP, and population). The equations obtained by means of the LMDI decomposition method are as follows:

$$\Delta N_{\mathrm{F}} = \Sigma_{ij}\ L\ (N_{ijT}, N_{ij0})\ \ln \left(\frac{F_T}{F_0} \right) \tag{5}$$

$$\Delta N_{\mathrm{MS}} = \Sigma_{ij}\ L\ (N_{ijT}, N_{ij0})\ \ln \left(\frac{MS_T}{MS_0} \right) \tag{6}$$

$$\Delta N_{\mathrm{MI}} = \Sigma_{ij}\ L\ (N_{ijT}, N_{ij0})\ \ln \left(\frac{MI_T}{MI_0} \right) \tag{7}$$

$$\Delta N_{\mathrm{IS}} = \Sigma_{ij}\ L\ (N_{ijT}, N_{ij0})\ \ln \left(\frac{IS_T}{IS_0} \right) \tag{8}$$

$$\Delta N_{\mathrm{R}} = \Sigma_{ij}\ L\ (N_{ijT}, N_{ij0})\ \ln \left(\frac{R_T}{R_0} \right) \tag{9}$$

$$\Delta N_{\mathrm{P}} = \Sigma_{ij}\ L\ (N_{ijT}, N_{ij0})\ \ln \left(\frac{P_T}{P_0} \right) \tag{10}$$

Where:

$$L\ (N_{ijT}, N_{ij0}) = (N_{ijT} - N_{ij0})\ /\ [\ln(N_{ijT}) - \ln(N_{ij0})] \tag{11}$$

We used these equations to analyze the scale effect (population), intensity effect (per capita GDP, material intensity), and structural effect (nitrogen content of the material, material consumption structure, industrial structure) generated by the various factors that affect Beijing’s anthropogenic nitrogen consumption. The contribution of each effect to the total characterizes the magnitude of the effect, and the sign indicates the direction of the effect (+ = promotion, – = inhibition). The contribution of a given factor is divided by the sum of the absolute values of the contribution values of all factors (which total to 1), so the contribution is standardized to fall within the range of [–1, 1], which we then converted from a decimal value within [–1, 1] to a percentage value.

3. Results

3.1 Analysis of Beijing’s anthropogenic nitrogen consumption

Beijing’s consumption of anthropogenic nitrogen shows two distinct periods: first, the total consumption increased steadily, with some variation, from 1995 to 2010, followed secondly, by a slow decreased thereafter (Fig. 2). Energy nitrogen matched this trend, but consumption of energy N proportion was always greater than 33% of the total and continued to grow throughout the study period. (Table S5 provides the actual values for Beijing’s nitrogen consumption structure from 1995 to 2015.) The proportions of energy nitrogen and fertilizer nitrogen at the beginning of the study were roughly equal (at about 38%), but energy nitrogen increased to 51% of the total by the end of the study period (Table S5). Growth of total nitrogen consumption also resulted from food nitrogen, which increased from 10% at the beginning of the study period to 21% by 2015 (Table S5). The reduction of total anthropogenic nitrogen consumption during the decreased period was mainly caused by the reduction of fertilizer nitrogen. It decreased throughout the study period, and its’ proportion during the later period was below that of food nitrogen, at 16 and 20%, respectively (Table S5). Feed nitrogen approximately doubled, but subsequently decreased to a value similar to that at the start of the study period. However, inorganic nitrogen changed little, fluctuating between 2% and 3% during the study period (Table S5).

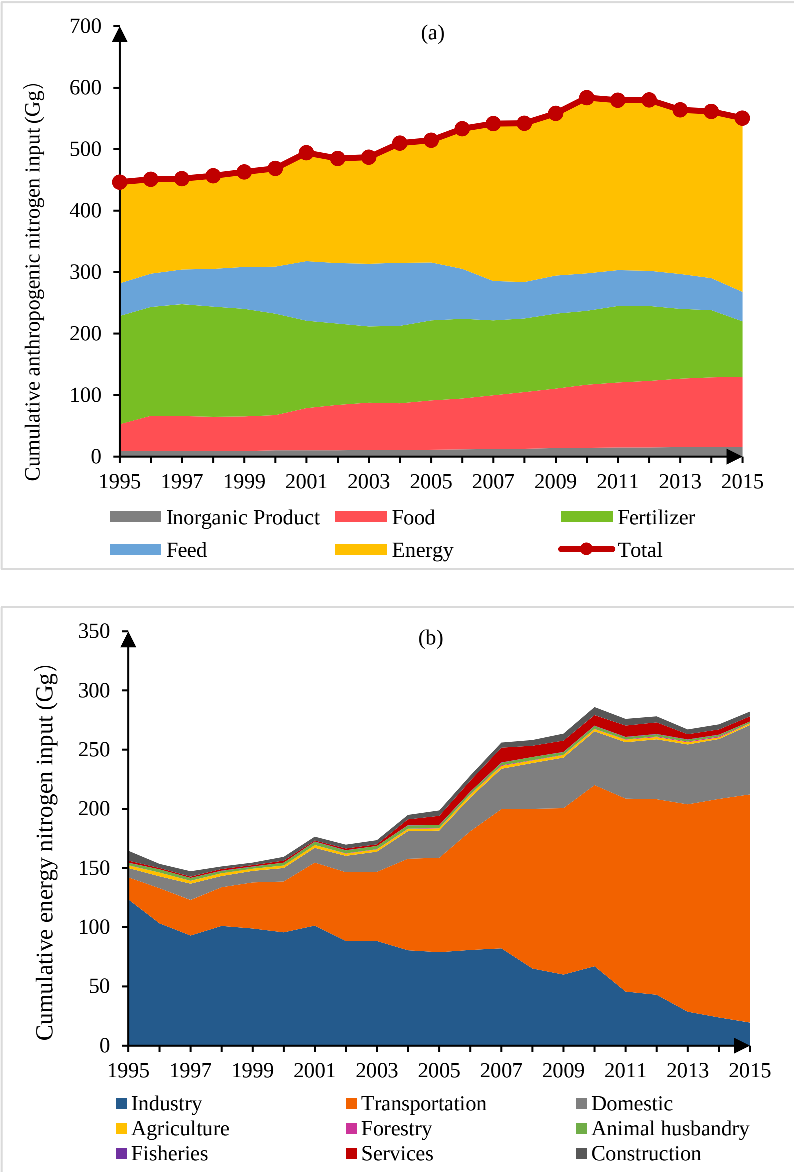

Fig. 2 (a) Total amount and structure of Beijing's anthropogenic nitrogen consumption and (b) energy nitrogen consumption by the main sectors. Table S5 shows the changes over time in the % of the total accounted for by each consumption sector in (a).

Overall, there were two important inflection points in Beijing's anthropogenic nitrogen consumption, in 2001 and 2010 (Fig. 2a). Total nitrogen consumption increased significantly in 2001, mainly driven by increased consumption of food nitrogen (14% of the total), feed nitrogen (20%), and energy nitrogen (36%). This is because Beijing's population has increased continuously during the study period (Fig. 3c), thereby increasing the demand for food (including animal products). In addition, Beijing's population increased dramatically in 2000 (Fig. 3c), by 8.5% compared with an average of 0.9% for the previous 4 years, and household income also continued to increase, permitting greatly increased consumption of high-nitrogen food such as meat. Beijing's total consumption of livestock and poultry peaked in 2001 (Fig. 3a), and its growth rate in 2001 (33.2%) was much higher than the average for the previous 5 years (14.6%). This increase naturally led to a sharp increase in total food nitrogen consumption in 2001 (Fig. 3a), when the growth rate of food nitrogen consumption reached 20.0%, which was much higher than the average for the previous 5 years (7.2%). At the same time, the increased livestock and poultry breeding greatly increased the feed nitrogen input, which was 27% higher than that in 2000. At the same time, the population growth increased domestic energy nitrogen consumption (Fig. 3d). In addition, during the early period of the 10^{th} 5-year plan (2001-2005), which had a planned target of 9% GDP growth, the energy nitrogen consumption of the industry and transportation sectors both increased significantly in 2001, resulting in a rapid increase of total energy nitrogen consumption (Fig. 2b). In summary, in 2001, the amount of anthropogenic nitrogen in Beijing reached a peak under the influence of various factors. Total domestic consumption increased along with the increasing population (Fig. 3c).

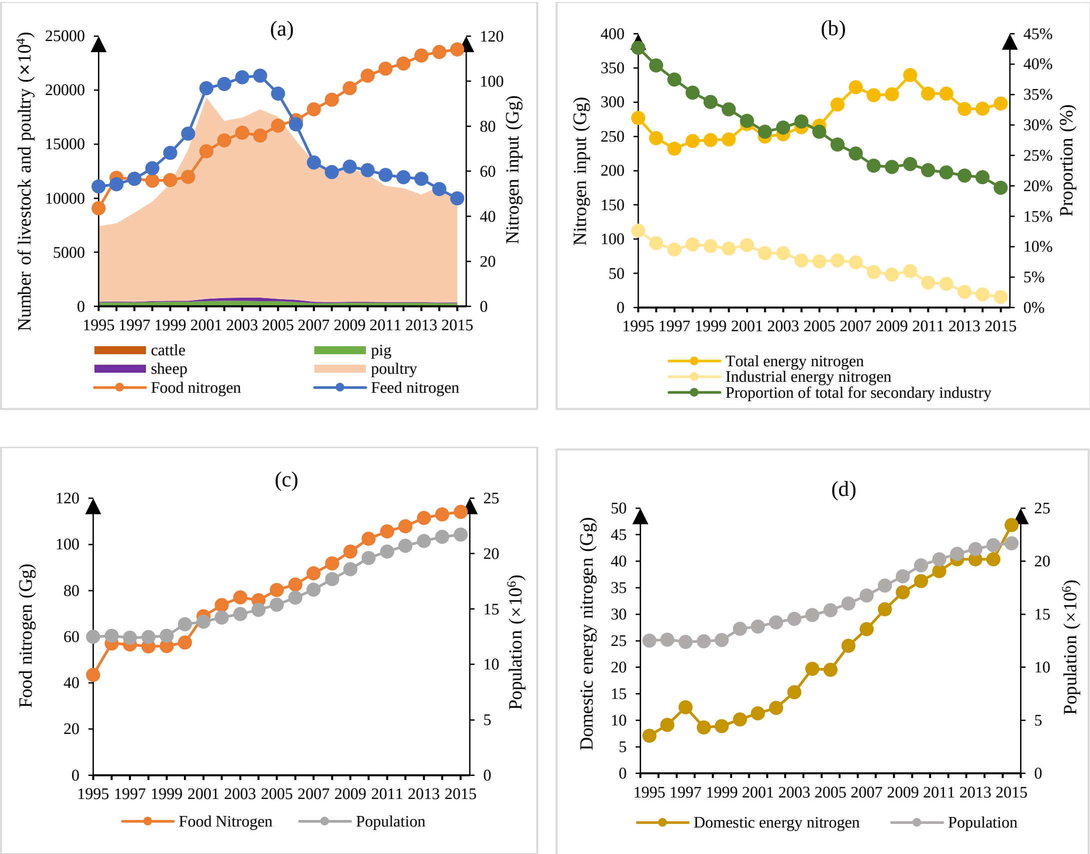

Fig. 3 Trends in Beijing's socioeconomic factors and nitrogen structures.

During the study period, Beijing has always responded to the state's requirements for industrial restructuring, and the proportion of the secondary industry has continued to decline. In addition, the government began preparing for the 2008 Olympics starting in 2002, and the proportion of secondary industry in Beijing reached its lowest value (28.9%) during the 11th 5-year plan period (from 2000 to 2005) (Fig. 3b). As a result, the industrial energy nitrogen consumption also decreased greatly, and the total energy nitrogen consumption also decreased in 2002 (Fig. 3b).

From 2002 to 2010, the growth of anthropogenic nitrogen consumption in Beijing accelerated and the average annual growth rate (2.2%) was much higher than that in the previous period (1.0%). In 2010, the total amount of anthropogenic nitrogen consumption in Beijing reached its peak, which was closely related to the growth of energy nitrogen (Fig. 2a). During the period of the 11th and 12th 5-year plans (2005 to 2010 and 2010 to 2015, respectively), construction of the urban transportation infrastructure accelerated, causing the demand for energy nitrogen to increase greatly (Fig. 2b). In 2010, Beijing's energy nitrogen consumption for transportation increased by 221% compared with the value in 2001. At the same time, the household energy nitrogen consumption also increased due to the continuous growth of Beijing's population, which increased by 41.6% in 2010 compared to the value in 2001 (Fig. 3d); as a result, household energy nitrogen consumption in 2010 increased by 2.2 times compared with the value in 2001. Together, these factors caused energy nitrogen consumption to increase rapidly and continuously. In addition, the population growth also increased food nitrogen consumption. Beijing's food nitrogen consumption increased by 48.5% between 2001 and 2010, and this component contributed greatly to the growth of total nitrogen consumption (Fig. 2a).

From 2011 to 2015, total nitrogen consumption decreased by a total of 33.6 Gg. These decreases resulted mainly from the reduction of feed, fertilizer and energy nitrogen consumption (reduced by 30.7Gg, 12.5Gg, and 3.7Gg, respectively. Fig. 2a). During the 12th 5-year plan period (2011 to 2015), the government planned further adjustments of the industrial structure, with the goal of reducing the proportions of primary and secondary industries and increasing the proportion of tertiary industries to more than 78%. This greatly reduced the fertilizer nitrogen, feed nitrogen, and industrial energy nitrogen required to support the primary and secondary industries, thus affecting Beijing's total nitrogen consumption.

3.2 Analysis of the factors that influenced Beijing's anthropogenic nitrogen consumption

Table 2 summarizes the promotion and inhibition of anthropogenic nitrogen consumption by the six driving factors. We divided Beijing's anthropogenic nitrogen consumption into three periods based on the two inflection points we observed (in 2001 and 2010): the first increasing period, the second increasing period, and the final decreasing period. From the perspective of the scale, intensity, and structural effects, the scale effect promoted the growth of anthropogenic nitrogen consumption, with the degree of the effect first increasing and then decreasing. The contribution of population to total N consumption was 5.5% during the first increasing period (1995-2000), 12.0% in the second increasing period (2001-2010), and 8.0% during the decreasing period (2011-2015), suggesting that the impact of population growth on Beijing’s consumption of anthropogenic nitrogen is too large to ignore. The direction of the intensity effect on anthropogenic nitrogen consumption changed during the study period, from promotion (with the material and per capita GDP intensity effects together totaling 19.9% of the total) during the first increasing period (1995 to 2000) to inhibition (- totaling -4.1%) during the decreasing period (2011 to 2015). This was mainly related to the continuous increase of inhibitory factors such as material intensity (whose contribution increased from 21.6% during the second increasing consumption period to 37.3% during the decreasing period) and the gradual weakening of promoting factors such as the per capita GDP (whose contribution decreased from 41.5% of the total during the first increasing period to 33.2% during the decreasing period). The overall structural effect (the sum of the nitrogen content, material consumption, and industrial structure components) always inhibited the growth of anthropogenic nitrogen consumption, but the magnitude of the inhibition decreased over time. This was caused by the fact that the inhibitory effect of the industrial structure (accounted for >14.0%) was much greater than the promotion effect of the nitrogen content of materials and the material consumption structure (which together accounted for <7.0%), and the strength of the inhibition of the industrial structure decreased greatly over time, while the strength of the promotion caused by the sum of the nitrogen content and material consumption structures increased.

Table 2 Standardized contributions of the factors that affected consumption of anthropogenic nitrogen from 1995 to 2015.

Effect	Factor	Promotion (positive %) or inhibition (negative %)		
		1995-2000	2001-2010	2011-2015
Structure	Nitrogen content of the material	2.14	3.63	6.90
	Material consumption structure	2.41	0.20	0.02
	Industrial structure	-26.85	-17.87	-14.60
Intensity	Material intensity	-21.63	-28.44	-37.31
	Per capita GDP	41.53	37.85	33.21
Scale	Population	5.45	12.02	8.00

Of the six factors that influenced consumption, only the material intensity and industrial structure showed inhibitory effects; the other four factors showed obvious promotion of nitrogen consumption. Material intensity and the industrial structure had similar inhibitory effects during the first increasing period (1995-2000), both accounting for more than 20% of the overall contribution. However, the inhibitory effect of material intensity continuously increased, whereas the effect of the industrial structure continuously weakened, decreasing to less than one-half of the contribution of material intensity during the period with decreasing nitrogen consumption (Table 2). Per capita GDP was the main driving force behind the growth of Beijing's anthropogenic nitrogen consumption. The contribution of this factor (41.5%) during the first increasing period was close to the sum of the contributions of material intensity and industrial structure. Although the contribution of per capita GDP decreased thereafter, it remained greater than 30% of the total contribution throughout the study period.

Population was also one of the main factors driving the growth of Beijing’s anthropogenic nitrogen consumption. However, the strength of its effect was volatile during the study period, with the contribution first doubling and then decreasing to about 67% of the peak value. The increase of the promotion effect also resulted from the amount of nitrogen in the materials. During the first increasing period, this promotion was similar to that of the structure of material consumption, with both contributions around 2%. During the decreasing period, the contribution of the nitrogen content of materials increased to 3.4 times its starting value, but the overall contribution remained less than 10%. The promotion effect of the material consumption structure decreased continuously, by 2 orders of magnitude. Taken together, the promotion effect of these two factors was small.

The promotion of the intensity effect mainly stems from the effects of per capita GDP, which is related to both population and GDP. However, the GDP growth rate was much larger than the population growth rate, and the ratio of GDP growth to population growth has decreased over time. (The ratio was 11.5% from 1995 to 2000, 10.4% from 2001 to 2010, and 5.7% from 2011 to 2015.) The gradual reduction in the strength of this effect can be attributed to the period of the 12th 5-year plan, during which China's economic development was expected to enter a "new normal" period with a gradual slowing of economic growth, accompanied by a focus on adjusting the economic structure and paying more attention to the quality of the economic development. The inhibitory effect of the material intensity factor, which represents the material consumption per unit of GDP, increased mainly because of the increasing material utilization efficiency. From 1995 to 2015, Beijing's energy consumption per unit GDP continued to decline, from 2.344 tce in 1995 to 0.338 tce in 2015 (BMBS, 1996, 2016). Meanwhile, Beijing's government issued a series of planning documents in 2017 to promote the development of high-tech industries such as information technology, integrated circuits, and the production of new energy-efficient automobiles with the goal of promoting scientific and technological innovation and improving material utilization efficiency. Thus, the inhibitory effect of material intensity factors will continue to increase.

The decreasing N consumption by Beijing's industrial sector resulted mainly from a change in the city's industrial structure. With the decreasing proportion of industry accounted for by Beijing's primary and secondary industries, the fertilizer nitrogen and feed nitrogen required by Agriculture and Animal Husbandry decreased by 48.9 and 9.9%, respectively (Fig. 2a). The energy nitrogen required by industrial production and the inorganic product nitrogen also decreased (Fig. 2a, 3b). With the increasing development of a tertiary industrial sector in the form of a service industry that increased from 52.5% of Beijing's GDP in 1995 to 79.7% in 2015 (BMBS, 1996, 2016), development of industries such as tourism, catering, and public transit would also lead to significant consumption of anthropogenic nitrogen. This can explain the increased consumption of food nitrogen and transportation energy nitrogen, which increased to 1.6 and 8.1 times the 1995 level, respectively (Fig. 2a,b). As a result, the strength of the inhibition of Beijing's anthropogenic nitrogen consumption by industrial structure factors decreased steadily, accounting for 26.9% of the inhibition during the first increasing period but only 14.6% during the decreasing period (Table 2, Fig. 4). The contribution of the material nitrogen content was consistently small (<10%), which may be related to the change of the material composition of feed, energy, inorganic products, and inorganic fertilizer. For example, as the standard of living improved due to growth in per capita GDP, the dietary structure of Beijing's residents underwent great changes. The proportion of food with a high nitrogen content (meat, eggs, and milk) increased from 15.5% in 1995 to 41.5% in 2015. The nitrogen content of materials also increased steadily, as did the corresponding promotion of consumption, resulting in a contribution of 2.1% in the first increasing period, 3.6% in the second increasing period, and 6.9% in the decreasing period (Table 2, Fig. 4). The effect of the material consumption structure was continuously small, accounting for less than 3.0% of the total, and less than 1.0% during the second increasing period and the decreasing period, which indicates that the changing material consumption structure had little influence on the increase of Beijing's anthropogenic nitrogen consumption.

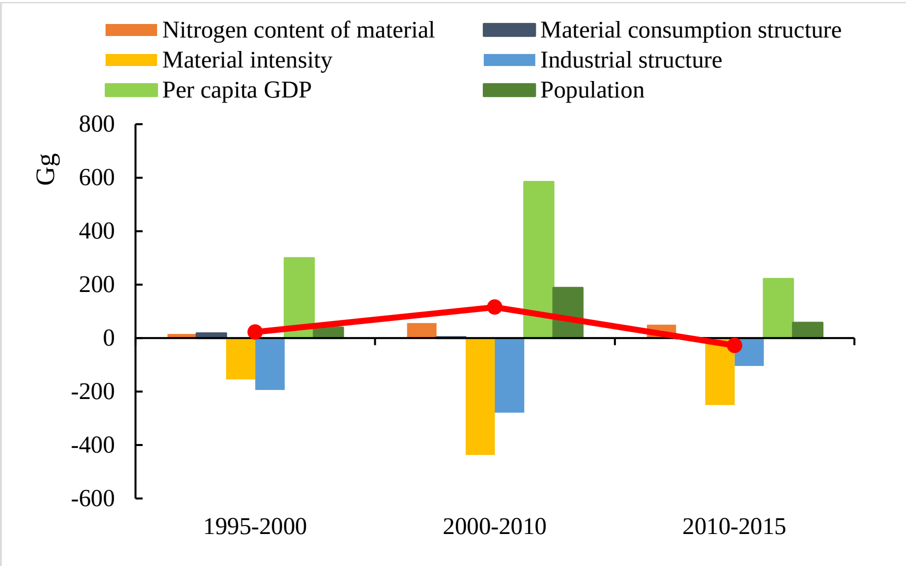

Fig. 4 Contributions of the factors that affected Beijing's nitrogen consumption from 1995 to 2015.

4. Discussion

Keeney (1979) proposed that it's essential that we be able to estimate nitrogen inputs, accumulation, and outputs caused by human activities. Subsequent researchers agreed. Vitousek et al. (1997) noted that systems constructed by humans, which differ greatly from natural ecosystems, have greatly affected the global nitrogen cycle. Galloway (1998) noted that the supply of reactive nitrogen in the global terrestrial ecosystem has doubled since 1860 due to human activities, mainly due to increased human demand for food and energy, resulting in extensive nitrogen accumulation. Baker et al. (2001) proposed that a detailed nitrogen budget is the starting point for understanding the nitrogen cycle of agricultural and urban ecosystems. Inputs lead to accumulation and emission, and indicators of anthropogenic nitrogen flows can characterize these flows from the source through consumption and emission, so nitrogen accounting can quantify these flows. Due to the large demand for matter and energy in cities, which function as concentrated areas of human activity, cities have become the world's most concentrated nitrogen sinks (Kaye et al., 2006). At the same time, analysis of the factors that influence anthropogenic nitrogen consumption has become an important tool for guiding efforts to reduce and control nitrogen consumption (Liu et al., 2014). Therefore, we analyzed anthropogenic nitrogen consumption and its structural characteristics in the present study, with the goals of identifying and quantifying the effects of the socioeconomic drivers behind this consumption and providing scientific support for efforts to improve the healthy development of urban ecosystems.

Table 3 compares the per capita anthropogenic nitrogen consumption in urban areas between the present study and previous research. The per capita consumption was greater than 32.0 kg annually in the three Chinese studies, including the present study. Only Phoenix had a comparable value, at 29.6 kg annually, and this value was at least 8% lower than the Chinese values. Phoenix has only about 20% of Beijing's population, and Phoenix's food, fertilizer, and energy consumption are less than 20% of Beijing's corresponding consumption, resulting in proportionally smaller nitrogen consumption in these categories. Shanghai's per capita anthropogenic nitrogen consumption was the lowest of the Chinese values, at 32.04 kg annually, which is slightly lower than the Chinese average level (32.12 kg annually in 2005). However, the accounting for Shanghai's nitrogen was not as comprehensive as in the present study, since it did not account for inorganic fertilizer nitrogen. The per capita anthropogenic nitrogen consumption in Chinese cities was slightly higher than the global average (about 29.0 kg annually), but much higher than the Asian level in 1995 (19.9 kg annually). This is because the level of urbanization in Asian countries is relatively low, leading to lower food and energy nitrogen consumption than the global average. The average per capita anthropogenic nitrogen consumption in Brazil at a national level was comparable to that at a city level in 1995 (30.9 kg annually), but by 2002, it had increased to 53.7 kg annually, which was much higher than the value in any of the other studies. This may be because of Brazil's unique geographical and climatic conditions; the warm climate leads to rapid plant growth and rapid decomposition of organic matter, and the poor-quality soils cannot retain nitrogen, leading to greatly increased need for supplemental nitrogen fertilizer. Even though its population was less than 15% of China's population in 2005, the nitrogen consumption of its agricultural products increased greatly to account for 94% of total nitrogen consumption, which is equivalent to nearly twice the value for China.

Table 3 Comparison of per capita anthropogenic nitrogen consumption in different regions of the world.

Area	**Source**	**Time**	**Annual per capita anthropogenic N consumption (kg)**
Global	Galloway et al. (2004)	1990	29.32
	Cui et al. (2013)	2005	28.77
Asia	Galloway & Cowling (2002)	1995	19.92
Brazil	Filoso et al. (2006)	1995	30.86
		2002	53.71
China	Cui et al. (2013)	2005	32.12
Phoenix	Baker et al. (2001)	1996	29.60
Hangzhou	Gu et al. (2009)	2004	34.02
Shanghai	Gu et al. (2009)	2004	32.04
Beijing	Present study	1996	35.82
		2004	34.16

Food and energy are two important components of the inputs of anthropogenic nitrogen (Galloway et al., 2004). Most of the variation observed in different studies (Table 4) can be attributed to different calculation methods as described below. Therefore, as we collect more and more case studies of nitrogen accounting, it will be useful to recommend standard methods. In 1996, Beijing's consumption of food nitrogen was slightly higher than that in Phoenix (1.2 times) during the same period. This resulted from different calculation methods for the nitrogen content in food. The Phoenix research calculated the nitrogen content based on the amount of protein required by different age groups, whereas the Beijing research calculated the nitrogen content based on the patterns of food consumption and the estimated nitrogen contents of the foods. Beijing's feed nitrogen consumption was more than 3 times that of Phoenix, mainly due to the fact that the Phoenix study only included livestock feed nitrogen for the production of dairy products, whereas the estimate for Beijing also included the nitrogen in livestock and poultry feed for the production of meat, eggs, and dairy. Hangzhou's food nitrogen in 2004 was about 70% of Beijing's value because the Hangzhou research only considered the biological nitrogen fixation of agricultural products, whereas the Beijing research included all food nitrogen consumption in agricultural products, including meat, eggs, and milk, but excluded biological nitrogen fixation. In contrast, the feed nitrogen consumption in Hangzhou was 1.5 times that of Beijing, mainly due to the larger number of livestock in Hangzhou (2.6 times that in Beijing), but the Beijing research also considered the nitrogen content of poultry and fish, decreasing the gap between the two estimates. The populations of the two cities also differed greatly, as Hangzhou's population was only 70% of Beijing's population (HMBS, 2004; BMBS, 2004), and this would also have narrowed the gap. The per capita food nitrogen consumption values for Xiamen, Shanghai, Toronto, and Paris were all more than 1.0 kg annually greater than Beijing's value in the same year, mainly due to the dietary structure of their residents. For instance, the proportion of nitrogen in fish, meat, and eggs (high-nitrogen foods) in Paris was 1.59 times that of Beijing in 2006. Moreover, unlike in most studies, the Toronto study calculated the per capita food nitrogen consumption based on protein consumption rather than the total diet.

Table 4 Comparison of the per capita inputs of food nitrogen, livestock feed nitrogen, and energy nitrogen in cities around the world.

City	**Source**	**Time**	**Urbanization rate (%)**	**Per capita food N (kg/year)**	**Per capita feed N (kg/year)**	**Per capita energy N (kg/year)**
Paris	Billen et al. (2012)	2006	-	8.07	-	-
Phoenix	Baker et al. (2001)	1996	77	3.67	1.30	13.46
Toronto	Forkes (2007)	2001	-	6.40	-	-
		2004	-	6.35	-	-
Shanghai	Gu et al. (2012)	2004	81.16	8.33	-	13.78
Hangzhou	Gu et al. (2009)	2004	43.4	3.55	10.0	5.03
Xiamen	Huang et al. (2016)	2008	68.28	7.21	-	16.41
Beijing	Present study	1996	76.06	4.53	4.30	12.2
		2004	79.53	5.08	6.86	13.06
		2006	84.33	5.16	5.05	14.25
		2008	84.9	5.18	3.37	14.58

In most cities, the per capita consumption of energy nitrogen was between 12 and 17 kg annually (Table 4). Hangzhou was the only exception, with a per capita energy nitrogen consumption only 40% of that in Beijing, whereas Shanghai had a slightly higher value than Beijing, at 1.06 times that of Beijing. These differences relate to differences in the energy consumption structure of each city. In 2004, the consumption of high-nitrogen oil accounted for 7.0% of Beijing's total energy consumption, at nearly double the proportion in Hangzhou (3.9%) (HMBS, 2004; BMBS, 2004). However, the consumption of low-nitrogen raw coal accounted for a large proportion of the total for Hangzhou (89.1%), resulting in a much lower per capita energy nitrogen consumption. Although Beijing's proportion of energy provided by oil was only 17% of the proportion in Shanghai, the proportion of high-nitrogen coke was much higher in Beijing (32.2% of the total, equivalent to 1.3 times the proportion in Shanghai, at 24.4%), greatly reducing the gap in per capita energy nitrogen consumption. The per capita consumption of energy nitrogen in Xiamen in 2008 was higher than in any other city, at 16.41 kg annually, but the total energy nitrogen consumption was less than 20% of that in Beijing during the same period, largely because Xiamen's population in 2008 was less than 20% of Beijing's population. These two effects compensated for each other to some extent, thereby reducing the gap between the two cities.

Beijing's per capita food nitrogen consumption increased noticeably when the urbanization rate was between 76 and 80%, whereas the per capita energy nitrogen consumption increased noticeably at an urbanization rate of 80 to 86%, peaking at an urbanization rate of 84.5% (Figure 5). At similar urbanization levels, Beijing's per capita food and nitrogen consumption were lower than those of Xiamen and Shanghai, but higher than that of Phoenix. Consumer-dominated cities such as Shanghai and Xiamen can learn from the government regulations designed to slow and then reverse Beijing's urbanization rate and per capita nitrogen consumption, as well as from the city's energy consumption structure. Combining the results of the Hangzhou study (Gu et al., 2009) with the present results suggests that with an increasing urbanization rate, the per capita nitrogen consumption increased, but that the magnitude of the increase differed among the urbanization levels. For example, when Hangzhou's urbanization rate increased from 25.0% to 43.4%, the per capita food and energy nitrogen consumption increased by about 0.06 kg annually for every 1% increase in urbanization rate (Gu et al., 2009). In contrast, when Beijing's urbanization rate increased from 83.6% to 86.5%, the per capita food nitrogen consumption increased by 0.12 kg/year for each 1% increase in urbanization, whereas the per capita annual consumption of energy nitrogen increased by 0.03 kg/year.

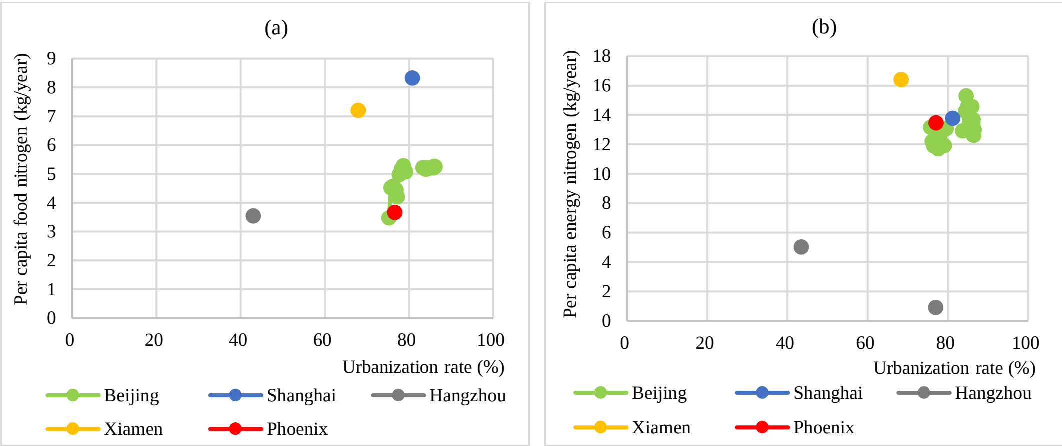

Fig. 5. Comparison of (a) per capita food nitrogen and (b) energy nitrogen input in each city. Data and their sources are shown in Table 4.

In previous research on the factors that influenced nitrogen consumption, analysis based on the LMDI method was divided into scale, structure, and intensity effects. The scale effects usually led to increased nitrogen consumption and emission (Liu et al., 2014). The economic scale factor was the main factor responsible for consumption and emission of anthropogenic reactive nitrogen, and the contribution was usually greater than 40% (Jia et al., 2017; Wang, 2017). This high proportion is determined by the economic development needs of these artificial systems. Our findings support these conclusions, as the scale effect always drove the growth of Beijing's anthropogenic nitrogen consumption (accounting for 5 to 12% of the total contribution). This is because we chose population as the size factor, and the economic scale was implicit in our choice of the per capita GDP factor. The per capita GDP was also the main factor (an intensity factor) driving the growth of Beijing's anthropogenic nitrogen consumption, accounting for more than 32% of the total during the study period.

In addition, most studies suggested that technological effects (Ding et al., 2017) and intensity effects (Lei et al., 2012) inhibited the growth of nitrogen consumption and emission, whereas the material intensity factor in the present study also showed high inhibition, accounting for more than 20% of the total. The direction of structural effects in previous research was usually divided into phases in which the change either promoted or inhibited consumption of reactive nitrogen (Wang, 2017), whereas the industrial structural effect observed in the present study consistently inhibited the growth of Beijing's anthropogenic reactive nitrogen consumption. This has resulted from the government's adjustment of Beijing's industrial structure to create a shrinking proportion of industries with high nitrogen consumption. This approach may be unique to Beijing's political and cultural status and may not be possible in all cities.

In view of the current situation of nitrogen consumption in Beijing and the main driving factors, our analysis suggests several possible policy recommendations. First, the government should continue its efforts to reduce the city's population and reduce the excessive resource consumption and environmental pollution caused by economic development. Because Beijing's government has realized the harm caused by the recent rapid population growth, and implemented a series of control measures, the city's population growth has slowed during the past 5 years, and the population's promotion of anthropogenic nitrogen consumption growth has decreased (Figure 4). For example, on 11 August 2016, Beijing implemented a points-based household registration system to further strengthen population control. However, since Beijing is China's capital and since the population is so high, it will be difficult to decrease the population. Therefore, we predict that population will continue to drive the growth of anthropogenic nitrogen consumption in Beijing for many years, although the strength of its promotion of nitrogen consumption will gradually decrease. Another future challenge is to scale up the recommendations for Beijing to a global population, if we want to gain control over nitrogen management.

In addition, in recent years, Beijing's attempts to develop a "circular" recycling economy and high-end tertiary industries have achieved good environmental benefits. The promotion of Beijing's anthropogenic nitrogen consumption by per capita GDP has weakened (Table 2, Figure 4). Therefore, it is necessary to adhere to the “3R” principle of a circular economy (reduce, reuse, recycle) and improve the material utilization efficiency to reduce anthropogenic nitrogen consumption and the associated nitrogen pollution. It is worth noting that in order to slow Beijing's economic development and reduce the population pressure on its environment, China’s national government officially established the Xiong’an New Area on 1 April 2017. This area will support functions other than those related to national government. With the completion of this separate area of the capital region, we expect that the promotion of anthropogenic nitrogen consumption by per capita GDP and population will be greatly reduced. Therefore, accelerating the move of Beijing residents to the Xiong'an New Area will begin to mitigate the problem of nitrogen consumption in Beijing.

5. Conclusion

In this study, we used empirical coefficients to represent the nitrogen contents of the materials consumed by Beijing’s urban system, and used statistical analysis to determine the quantities of these materials from 1995 to 2015. Multiplying the two values quantified Beijing’s anthropogenic nitrogen consumption and let us analyze the changes of the consumption structure, thereby providing a deeper understanding of the city’s consumption of anthropogenic reactive nitrogen. These results provide important data to support efforts to control the city’s nitrogen consumption. The LMDI method let us quantify the magnitude and direction of the impact of the socioeconomic drivers on Beijing’s total nitrogen consumption, and provided important decision variables to guide control measures for urban nitrogen consumption. For example, the government's decision to replace primary and secondary industries with tertiary industries greatly reduced the energy nitrogen consumption, and such forms of management could be applied in other cities with a high energy nitrogen consumption. Our results therefore demonstrate the usefulness of this method due to its ability to reflect the changing characteristics of urban nitrogen consumption and the impacts of human activities on this consumption. However, such efforts must be managed so that they do not only move a problem to a new location. The adage of "think globally, act locally" apply as we address nitrogen management at a global level. For example, inefficient older technologies should be replaced by newer and more efficient technologies that reduce nitrogen consumption and the associated pollution.

We found that Beijing's anthropogenic nitrogen consumption increased steadily from 1995 to 2010, and then decreased steadily, mainly due to changes in consumption of energy nitrogen, food nitrogen, and inorganic fertilizer nitrogen. The changes in consumption of energy nitrogen, which accounted for more than 33% of the total throughout the study period, had the greatest impact on the total consumption. Food nitrogen continued to increase, reaching more than 20% of the total, whereas inorganic fertilizer nitrogen decreased below 20% of the total. Beijing's increasing per capita GDP greatly increased anthropogenic nitrogen consumption, accounting for more than 30% of the total, and the promotion effect of the material consumption structure decreased by two orders of magnitude, reaching only 0.02% by the end of the study period, whereas the inhibition that resulted from changes in the industrial structure remained greater than 15% of the total. The inhibitory effect of the material intensity on nitrogen consumption has been greater than 20% and continues to increase.

There are still some shortcomings in our research. Due to data limitations, we used interpolation to estimate some missing data. The accuracy of the data also needs to be improved. For example, the consumption of certain chemical substances in some years was not available. We estimated the anthropogenic nitrogen consumption for these missing chemical substances in combination with the proportion of population in Beijing. There is also inadequate data for the city's recycling system. If the actual chemical consumption data can be obtained through future empirical research, then the accuracy of the results will improve. In addition, in terms of our analysis of the factors that influence nitrogen consumption, our factor decomposition model considered only six factors for which comprehensive data were available. If more detailed data can be collected on additional factors, then the impact of factors such as the industrial structure could be refined to account for more industrial sectors and more types of nitrogen-containing materials, thereby providing finer resolution and deeper insights into the structural characteristics of each sector and each category of materials. This would let us establish a more detailed model that could be used to compare the development characteristics of various cities, thereby improving our ability to understand differences in the processes that drive urban ecological development. Given the importance and frequency with which such studies are being conducted, we also promote transparency and consistency of methods and data collection to make for easier comparison of the various case studies. This improved data would also provide greater support for efforts to identify industries with the greatest consumption of nitrogen so that efforts could be made to reduce their nitrogen consumption.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (no. 41871213), and by the Fund for Innovative Research Group of the National Natural Science Foundation of China (no. 51721093).

References

Ang, B.W., 2004. Decomposition analysis for policymaking in energy: which is the preferred method? Energ. Policy 32, 1131–1139.

Baker, L.A., Hope, D., Xu, Y., Edmonds, J., Lauver, L., 2001. Nitrogen balance for the Central Arizona–Phoenix (CAP) ecosystem. Ecosystems 4, 582–602.

Billen, G., Barles, B., Chatzimpiros, P., Garnier, J., 2012. Grain, meat and vegetables to feed Paris: where did and do they come from? Localising Paris food supply areas from the eighteenth to the twenty-first century. Reg. Environ. Change 12, 325–335.

Billen, G., Garnier, J., Lassaletta, L., 2013. The nitrogen cascade from agricultural soils to the sea: modelling nitrogen transfers at regional watershed and global scales. Philos. Trans. R. Soc. B368, 1621.

Billen, G., Garnier, J., Mouchel, J. M., Silvestre, M., 2007. The Seine system: introduction to a multidisciplinary approach of the functioning of a regional river system. Sci. Total Environ. 375(1), 1-12.

BMBS and NBS (Beijing Municipal Bureau of Statistics, National Bureau of Statistics Survey Office), 2016. Beijing Statistical Yearbook 1996–2016. China Statistics Press, Beijing (in Chinese).

Cui, S.H., Shi, Y.L., Groffman, P.M., Schlesinger, W.H., Zhu, Y.G., 2013. Centennial-scale analysis of the creation and fate of reactive nitrogen in China (1910–2010). Proceedings of the National Academy of Sciences of the USA, 110 (6), 2052-2057.

Deng, M.H., Xie, Y.X., Xiong, Z.Q., 2007. Nitrogen budgets of the Yangtse delta region and their effect on the environment (in Chinese with English summary). Acta Scientiae Circumstantiae, 27(10), 1709-1716.

Ding, L., Liu, C., Chen, K.L., Huang, Y.L., Diao, B.D., 2017. Atmospheric pollution reduction effect and regional predicament: an empirical analysis based on the Chinese provincial NO_x emissions. J. Environ. Manage. 196, 178-187.

EBCAIY (Editorial Board of China Animal Industry Yearbook), 2016. China Animal Industry Yearbook 1996-2016. China Agriculture Press, Beijing (in Chinese).

EBCAIY (Editorial Board of China Animal Industry Yearbook), 2016. China Animal Industry Yearbook 1996-2016. China Agriculture Press, Beijing (in Chinese).

Filoso, S., Martinelli, L.A., Howarth, R.W., Boyer, E.W., Dentener, F., 2006. Human activities changing the nitrogen cycle in Brazil. Biogeochemistry 79, 61-89.

Forkes, J., 2007. Nitrogen balance for the urban food metabolism of Toronto, Canada. Resour. Conserv. Recy. 52, 74–94.

Galloway, J.N., 1998. The global nitrogen cycle: changes and consequences. Environ. Pollut. 102, 15-24.

Galloway, J.N., Cowling, E.B., 2002. Reactive nitrogen and the world: 200 years of change. AMBIO. 31(2), 64-71.

Galloway, J.N., Dentener, F.J., Capone, D.G., Boyer, E.W., Howarth, R.W., Seitzinger, S.P., Asner, G.P., Cleveland, C.C., Green, P.A., Holland, E.A., Karl, D.M., Michaels, A.F., Porter, J.H., Townsend, A.R., Vorosmarty, C.J., 2004. Nitrogen cycles: past, present, and future. Biogeochemistry 70, 153–226.

Galloway, J.N., Theis T.L., Doering, O.C., 2015. Managing Nitrogen Pollution in the United States. Air & Waste Management Association 9: 6-11

Galloway, J.N., Townsend, A.R., Erisman, J.W., Bekunda, M., Cai, Z.C., Freney, J.R., Martinelli, L.A., Seitzinger, S.P., Sutton, M.A., 2008. Transformation of the nitrogen cycle: recent trends, questions, and potential solutions. Science 320, 889-892

Gao, B., Huang, Y.F., Huang, W., Shi, Y.L., Bai, X.M., Cui, S.H., 2018. Driving forces and impacts of food system nitrogen flows in China, 1990 to 2012. Sci. Total Environ. 610-611, 430-441.

Gao, C.K., Gao, W.G., Song, K.H., Na, H.M., Tian, F., Zhang, S.B., 2019. Spatial and temporal dynamics of air-pollutant emission inventory of steel industry in China: A bottom-up approach. Resour. Conserv. Recy. 143, 184-200

Gao, W., Guo, H.C., Hou, X.K., 2014a. Evaluating City-Scale Net Anthropogenic Nitrogen Input (NANI) in Mainland China (in Chinese with English summary). Acta Scientiarum Naturalium Universitatis Pekinensis, 50(5), 951-959

Gao, W., Howarth, R.W., Hong, B., 2014b. Estimating net anthropogenic nitrogen inputs (NANI) in the Lake Dianchi basin of China. Biogeosciences 11(16), 4577-4586.

Gu, B.J., 2011. Human–Natural Cycle of Natural Coupling System--A Case Study of China, Ph.D. Thesis. Zhejiang University, Zhejiang, China (in Chinese).

Gu, B.J., Chang, J., Ge, Y., Ge, H., Yuan, C., 2009. Anthropogenic modification of the nitrogen cycling within the Greater Hangzhou Area system, China. Ecol. Appl. 19, 974-988.

Gu, B.J., Dong, X.L., Peng, C.H., Luo, W.D., Chang, J., Ge, Y., 2012. The long-term impact of urbanization on nitrogen patterns and dynamics in Shanghai, China. Environ. Pollut. 171, 30-37.

HMBS (Hangzhou Municipal Bureau of Statistics), 2016. Hangzhou Statistical Yearbook 1996–2016. China Statistics Press, Hangzhou (in Chinese).

Huang, W., Cui, S.H., Yu, Y., Gao, B., Bai, X.M., 2016. Urban nitrogen metabolism in Xiamen City, China. p.1-5 In: Cameron Gourley (ed.). Proceedings of the 2016 International Nitrogen Initiative Conference, "Solutions to improve nitrogen use efficiency for the world", 4 – 8 December 2016, Melbourne, Australia.

Jia, J.S., Jian, H.Y., Xie, D.M., Gu, Z.Y., Chen, C.D., 2017. Multi-perspectives' comparisons and mitigating implications for the COD and NH_3-N discharges into the wastewater from the industrial sector of China. Water-sui 9(3), 1-18.

Jordan, T. E., Weller, D. E., 1996. Human contributions to terrestrial nitrogen flux. BioScience 46(9), 655-664.

Kato, N., Akimoto, H., 1992. Anthropogenic emissions of SO_2 and NO_x in Asia—emission inventories. Atmos. Environ. A–General, 26, 2997–3017.

Kaye, J.P., Groffman, P.M., Grimm, N.B., Baker, L.A., Pouyat, R.V., 2006. A distinct urban biogeochemistry? Trends Ecol. Evol. 21, 192-199.

Keeney, D.R., 1979. A mass balance of nitrogen in Wisconsin. Transactions of the Wisconsin Academy of Sciences, Arts, and Letters 67, 95-102.

Lei, H.J., Li, C.J., Xia, X.F., Xi, B.D., 2012. Decomposing the influencing factors of China's industrial wastewater discharges using LMDI I method (in Chinese with English summary). Advances in Environmental Science and Engineering 518-523, 2089-2098.

Li, C.J., Lei, H.J., Pan, C.Z., Ding, A.Z., Yan, Z.H., Cui, S.C., 2012. Decomposing the influencing factors of COD and NH_4-N discharged in industrial water environment (in Chinese with English summary). Journal of Beijing Normal University (Natural Science) 48(5), 476-482.

Liu, C., Fei, J.L., Hayashi, Y., Yasunari, T., 2014. Socioeconomic driving factors of nitrogen load from food consumption and preventive measures. AMBIO 43(5), 625-633.

Luo, Z.B., Hu, S.Y., Chen, D.J., Zhu, B., 2018. From production to consumption: a coupled human−environmental nitrogen flow analysis in China. Environ. Sci.

Technol. 52, 2025−2035

Ma, L., Ma, W.Q., Velthof, G.L., 2010. Modeling nutrient flows in the food chain of China. J. Environ. Qual. 39(4), 1279-1289.

MAC (Ministry of Agriculture), 2016. China Agriculture Statistical Report. China Agriculture Press, Beijing (in Chinese)

NBS and MEP (National Bureau of Statistics, Ministry of Environmental Protection), 2016. China Statistical Yearbook on the Environment 1996-2016. China Statistics Press, Beijing (in Chinese).

NBSC (National Bureau of Statistics Department of Energy Statistics), 2016a. China Energy Statistical Yearbook 1996-2016. China Statistics Press, Beijing (in Chinese).

NBSC (National Bureau of Statistics Department of Industry Statistics), 2016b. China Industry Economy Statistical Yearbook 1996-2016. China Statistics Press, Beijing (in Chinese).

NBSC (National Bureau of Statistics Department of Rural Social Economic Investigation), 2016c. China Rural Statistics Yearbook 1996-2016. China Statistics Press, Beijing (in Chinese).

NBSC (National Bureau of Statistics of China), 2016d. China Statistical Yearbook 1996-2016. China Statistics Press, Beijing (in Chinese).

Pang, J., Shi, Y.C., Hu, T., Yan, Y.N., Liang, L.N., 2013. Structural decomposition analysis of pollutants emission change embodied in exports of China (in Chinese with English summary). China Environmental Science, 33(12), 2274-2285.

Ti, C.P., Pan, J.J., Xia, Y.Q., Yan, X.Y., 2012. A nitrogen budget of mainland China with spatial and temporal variation. Biogeochemistry 108, 381–394.

UN-DEAS, 2015. World Urbanization Prospects: the 2014 Revision. United Nations, Department of Economic and Social Affairs, Population Division, 2015.UN. World Urbanization Prospects: The 2014 Revision, Highlights, ST/ESA/SER.A/352.

Vitousek, P.M., et al., 1997. Human alteration of the global nitrogen cycle: sources and consequences. Ecol. Appl. 7, 737–750.

Wang, L. Q., 2017. Investigation of NO_x emissions reduction and its strategies over China's 30 provinces based on LMDI (in Chinese with English summary). Acta Scientiae Circumstantiae, 37(6), 2394-2402.

Yu, Y., Cui, S.H., Zhao, S.N., Meng, F.X., Fei, L., 2012. Changes of residents' nitrogen consumption and its environmental loading from food in Xiamen (in Chinese with English summary). Acta Ecologica Sinica, 32(19), 5953-5961.

Zhang, W.S., Li, X.Y., Swaney, D.P., Du, X.Z., 2016a. Does food demand and rapid urbanization growth accelerate regional nitrogen inputs? J. Clean. Prod. 112, 1401-1409.

Zhang, Y., Lu, H.J., Zheng, H.M., 2016b. A review of multiple-scale nitrogen cycle and nitrogen metabolism with the influence of human activities (in Chinese with English summary). China Population Resources and Environment, 26(11), 417-422.

Zhou, M.H., Brandt, P., Pelster, D., Rufino, M.C., Robinson, T., Butterbach-Bahl, K., 2014. Regional nitrogen budget of the Lake Victoria Basin, East Africa: syntheses, uncertainties and perspectives. Environ. Res. Lett. 9, 105009.