Pol. J. Environ. Stud. Vol. 29, No. 1 (2020), 763-777
DOI: *10.15244/pjoes/99979* ONLINE PUBLICATION DATE: 2019-09-09

Original Research

Evolution and Driving Forces of Non-Point Source Pollution in a Developing Megacity: Beijing as a Long-Term Case Study

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Received: 15 October 2018
Accepted: 25 November 2018

Abstract

Nonpoint source pollution (NPSP) is a serious environmental problem faced by megacities throughout the world. Unlike small cities, problems associated with NPSP are more complex in developing megacities. However, long-term spatial and temporal variations in NPSP, as well as the driving forces behind these changes, are still unknown for a developing megacity. In this study, we used a model set containing export coefficients and statistical models to calculate NPSP load for five NPSP types from 2006 to 2016 in Beijing and its four city functional zones. Our results indicate that the total NPSP decreased by 8.1% from 2006 to 2016. Agricultural NPSP was the largest source of NPSP and measured 46.2% in 2016. Agricultural NPSP, livestock NPSP and soil erosion NPSP decreased by 19.1%, 38.7%, and 0.8%. However, urban NPSP and rural NPSP increased by 10.8% and 8.5%. In the four functional zones, urban NPSP in the capital function core zone decreased by 17.3%, total NPSP in the urban functional development zone increased by 43.0%, total NPSP in the urban development fresh zone decreased by 13.1% and total NPSP in the ecological conservation development zone decreased by 14.7%. The urban functional development zone was key to preventing future NPSP.

Keywords: NPSP, developing megacity, spatial and temporal variation, driving forces, remote sensing

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Introduction

Nonpoint source pollution (NPSP) is a serious environmental problem not only in agricultural regions but in urban regions throughout the world. NPSP degrades vital water resources and deprives natural systems and their component species [1-2]. NPSP has been categorized into many types based on specific pollution sources, including agricultural NPSP [3-4], urban NPSP [5], livestock NPSP [6-7], rural NPSP [8], and soil erosion NPSP [9]. Agricultural NPSP and urban NPSP have been given more attention because they have a direct and significant impact on environmental quality, human health, and urban planning [10-11]. Compared with agricultural NPSP, urban NPSP has a longer research history that extends back to the 1972 Federal Water Pollution Control Act [12], but due to its unique characteristics it has a slower rate of improvement relative to agricultural NPSP.

Urban NPSP has three significant features: complex components, a correlation with human activities and a susceptibility to policy and urban planning. Unlike agricultural NPSP, which is primarily concerned with nitrogen and phosphorus [13-14], urban NPSP contains very complex components that may include COD (chemical oxygen demand), BOD (biochemical oxygen demand), nitrogen (NH_4, NO_3 and total nitrogen), and phosphorus (dissolved phosphorus, total phosphorus) [15-16]. This complexity is the result of two factors. First, urban areas contain more pollution sources, such as artificial waste, and these components are very unpredictable. Second, the land use and land cover is very complex and may include dozens of land use types particular to a megacity [17]. In addition, human activity is more strongly correlated with urban NPSP relative to agricultural NPSP. Urban NPSP loads are influenced by human activities such as construction, city sanitation and public traffic. At the same time, human experiences are influenced by NPSP pollution, as in the case of city river eutrophication [18]. Urban NPSP is also influenced by policy and urban planning because of strong relationships with residents. For example, it can be influenced by changes in policy (e.g., environmental act) and urban planning (e.g., urban planning for the Olympic Games). Policy and planning have the ability to change the NPSP load over the short-term.

Previous research regarding urban NPSP has focused on the driving forces behind spatial and temporal variations in small cities and communities and in the short-term (i.e., rainfall events). However, the driving forces behind spatial and temporal variations in NPSP over the long-term, and for a developing megacity, are unclear. Ventura and Kim (1993) [19] modeled urban nonpoint source pollution in a 12.4 km^2 area in Dodge County, Wisconsin. Tsihrintzis and Hamid (1998) calculated NPSP in four relatively small urban sites (5.97-23.56 ha) in southern Florida. Mitchell (2005) [20] calculated the urban watershed NPSP in the Aire basin, Yorkshire, U.K., to be 2,057 km^2. Chen et al. (2008) [8] calculated NPSP for a 42 km^2 urban-rural area in Hangzhou city, China. Ping et al. (2013) [21] simulated NPSP in Minyun County, located in Beijing, in a 1010 km^2 area.

It is difficult to obtain information ofNPSP from a single method owing to there being multiple NPSP types. Statistical models, export coefficients models, semi-mechanism models, and mechanism models have been frequently used to obtain the urban NPSP. Statistical models have been used to build relationships between NPSP load and land surface information or runoff, such as the PARROW model [22-23]. Coefficient models have been used to describe the mass pollutant load delivered to the stream edge for a particular land use. The models were based on empirical studies of transit loss and measurements of nutrient loads [24]. Semi-mechanism models integrate empirical and mechanism models, such as SWMM [25]. Mechanism models, such as the BASINS model [26], are based on the physical and chemical mechanism of generation and cycle. Semi-mechanism models and mechanism models need rigorous input data, thus these two models have been used for the small city or community scale. For the megacity scale, simple statistical models and coefficient models offer advantages in data preparation. Statistical models require less data compared with mechanical models, which is crucial given that data collection in megacities is difficult.

The objectives of this paper are to obtain the multi-NPSP types from 2006 to 2016 for Beijing by using an NPSP model set of export coefficients and statistical models, address spatial and temporal variations in NPSP over the long-term for a megacity and examine the driving forces behind spatial and temporal variations in NPSP. In this paper, the study area and the calculation method for NPSP are described, the NPSP results for the two periods and their spatial distribution are presented, and the driving forces are discussed based on detailed surveys and statistical data.

Material and Methods

Study Domain

Beijing is a megacity that serves as the capital of China. It has an area of 16,807.8 km^2 and is located within 39.4-41.6°N, 115.7-117.4°E (Fig. 1). Beijing is located in a temperate climatic zone with mean annual temperature of 12ºC and annual average precipitation of 640 mm. Beijing is located in the northern part of the northern China plain [27], which includes 16 districts and counties (Fig. 1). Topographically, Beijing is characterized by mountains in the northwest, which account for 62% of the total area, and the "Beijing Plain" in the southeast, which accounts for 38% of the total area; the elevation is lower than 100 m [28]. Though more than 200 rivers flow through this city, water depletion is a continuous problem because it is located in a semi-arid area with large water demand. Natural vegetation in this area is deciduous broadleaf forest (e.g., *Populustomentosa, Betulaplatyphylla*), evergreen coniferous forest (e.g., *Pinustabulaeformis, Quercusacutissima*), and bush grass. However, most of the original natural vegetation has been removed due to human activity and urban development.

Over the past few decades, Beijing has experienced rapid urbanization and further encroachment into the surrounding countryside. In 2016, Beijing had a population of 21.7 million with an average population density of 1,324 persons/km^2 [29]. Because of rapid urban expansion and population growth, Beijing has experienced intensive land-use changes from natural land to construction land [30]. In 2012, the total area of Beijing was divided into four functional zones (Fig. 1). The capital functional zone (Dongcheng District and Xicheng District) played the role of capital. The urban functional development zone (Haidian District, Shijingshan District, Fengtai District, Chaoyang District) played the role of financial and international exchange. The urban development fresh zone (Fangshan District, Tongzhou District, Shunyi District, Changping District, Daxing District) played the role of manufacturing and modern agriculture. The ecological conservation development zone (Yanqing District, Miyun District, Mentougou District, Huairou District, Pinggu District) provided an ecological barrier for Beijing (Fig. 1).

Algorithms of NPSP Calculation

Due to Beijing's large area and complex urban components, NPSP were classified into five types, including rural NPSP, agricultural NPSP, livestock NPSP, soil erosion NPSP, and urban NPSP. These five NPSP types were the main nonpoint source pollution types for Beijing. We focused on the four leading contaminants associated with NPSP pollution, including COD (chemical oxygen demand), NH_4, TN (total nitrogen), and TP (total phosphorus).

In this study, an NPSP model set of export coefficient models [31-32], and statistical models [33] was used to calculate the five NPSP loads for Beijing. The function details used in this study are displayed in Table 1. There are two reasons for using a model set instead of one model. First, diverse NPSP types not only include traditional urban NPSP but also cover agricultural NPSP; complex land surface conditions and a large population make it difficult to calculate NPSP load in just one model. Second, complex physical models like the SWMM model [34] are often used to calculate the urban NPSP, but it can be difficult to collect input data to satisfy the model completely in the long term. For example, it is not possible to obtain the pipeline data for Beijing because of legal restrictions.

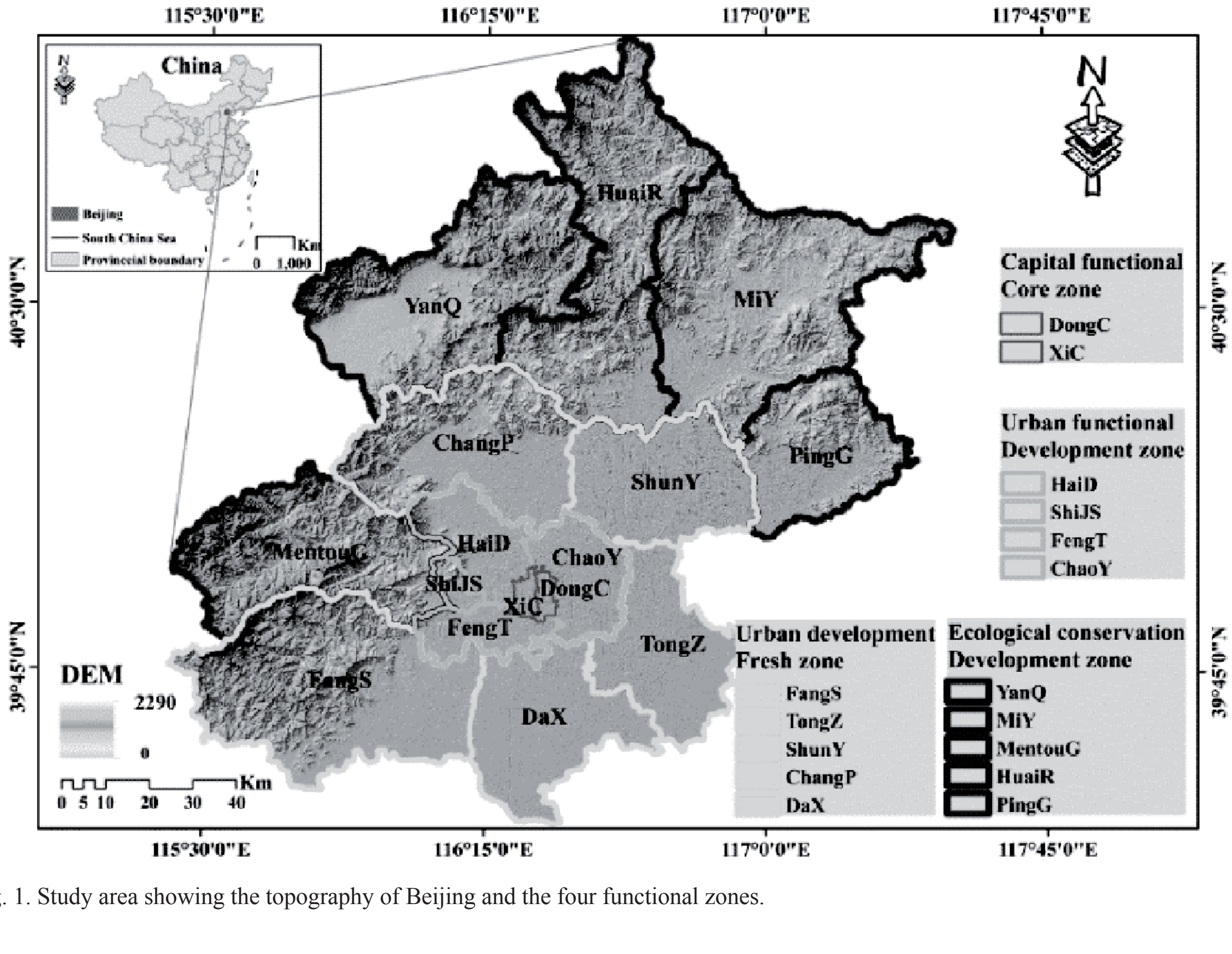

Fig. 1. Study area showing the topography of Beijing and the four functional zones.

Table 1. NPSP model set and functions used in this study.

Number	NPSP module	Functions	References
1	Rural NPSP Agricultural NPSP Livestock NPSP	$L=\sum_{i=1}^{n}\alpha\beta E_i[A_i(I_i)]+p$ $\alpha=\alpha_t\cdot\alpha_s=\frac{R_i\cdot R_j}{\bar{R}\cdot\bar{R}}$ $\beta=\frac{L(\theta_j)}{L(\bar{\theta})}=\frac{c\theta_j^{\,d}}{c\bar{\theta}^{d}}=\frac{\theta_j^{\,d}}{\bar{\theta}^{d}}$ $E_h=D_a\times H\times 365\times M\times B\times R_S\times C$ $p=c\times a\times Q$ $L=c\theta^{d}$	[31-33]
2	Soil erosion NPSP	$\omega=\sum\ \omega_i\times A_i\times ER_i\times c_i\times 10^{-6}$	[33]
		$\omega_i=11.8\ (Q_{surf}\ q_{peak}\ area_{pixel})^{0.56}$ $K\ C\ LS\ CFRG$	[33]
3	Urban NPSP	$L=R\times C_{NPS}\times A\times 10^{-6}$	[32]

Annotations: L: amount of NPSP load (t), α: rainfall influence factor, β: topographical factor, E_i: export coefficient, A_i: area of land use or amount of population or livestock (km^2 or 10^4), I_i: input of NPSP (t), p: NPSP from rainfall (t), α_t: rainfall time influence factor, α_s: rainfall space distribution influence factor, R_i: mean monthly rainfall for one space unit ini^{th} month (mm), R_j: annual rainfall for the j^{th} space unit (mm), $\bar{R}$: mean annual rainfall for the entire area (mm), θ_j: slope of the j^{th} space unit (ºC), $\bar{\theta}$: mean slope for the total area (ºC), c: constant factor, d: constant factor, E_h: NPSP export from population per year (t), D_{ca}: NPSP export per person in one day (t), H: total population in the whole area (10^4), 365: days in one year, M: NPSP deduction by physical process (0.85-0.9), B: NPSP deduction by biological process (0.8-0.9), R_s: retention coefficient of NPSP in the filter tank (0.1-0.8), C: P deduction coefficient (0.1-0.2), c NPSP concentration in the rainfall (mg/L), α: rainfall in the whole area (m^3), Q: ratio of runoff and rainfall, ω: the amount of NPSP from soil erosion (t), ω_i: soil erosion in one land-use type (t/km^2), ER_i: enrichment factor, c_i: the concentration of NPSP in the soil (t/km^2),sed: Sediment yield on a given day (t),Qsurf: Surface runoff volume (mm),qpeak: Peak runoff rate (m3/s), area pixel: Area of the pixel (km^2), K: soil erodibility factor, C: The cover and management factor, P: Support practice factor, LS: topographic factor, CFRG: coarse fragment factor, R: annual runoff (mm), C_{NPS}: the mean concentration of NPSP in the runoff (mg/L).

Results and Discussion

Temporal and Spatial Variations in NPSP from 2006 to 2016

Five Beijing NPSP pollution loads, from 2006 to 2016, are shown in Fig. 2. From 2006 to 2016, the total NPSP amount for a single year decreased by 8.1%, from 234,700 t in 2006 to 215,709 t in 2016. For the five types of NPSP pollution, agricultural NPSP was the dominant NPSP type. In 2006 and 2016, 52.3% and 46.2% of the total NPSP was agricultural NPSP, respectively. The three largest NPSP types, in order of total contribution, were agricultural NPSP > urban NPSP > soil erosion NPSP. In 2006, livestock NPSP was 2.0% and was higher relative to the rural NPSP. However, this reversed in 2016 with livestock NPSP measuring 1.3%. From 2006 to 2016, agricultural NPSP, livestock NPSP and soil erosion NPSP decreased by 19.1%, 38.7%, and 0.8%, respectively; livestock NPSP has decreased considerably. Urban NPSP and rural NPSP have increased by 10.8% and 8.5%, respectively.

Four of the five NPSP types displayed variations in pollution elements from 2006 to 2016 (Fig.2). For the rural NPSP, all four elements increased from 2006 to 2016 and the increasing NPSP was largely similar year to year but reached a maximum of 8.5%. For agricultural NPSP, TN was the leading element and accounted for 65.8% in 2006 and 59.2% in 2016. All four elements in agricultural NPSP declined from 2006 to 2016. TN decreased the most and reached 27.2% of the total. Livestock NPSP showed a significant decrease over the study period and COD, NH_4, TN and TP decreased by 46.4%, 51.0%, 28.1% and 19.5%, respectively. TN was still the main pollution element in the livestock NPSP. Soil erosion NPSP did not display obvious variations though the total amount was large. COD was the main element in soil erosion NPSP and it measured 76.7% in 2006 and 72.8% in 2016. COD and TP decreased by 5.7% and 9.8%, but the NH_4 and TN increased by 6.0%

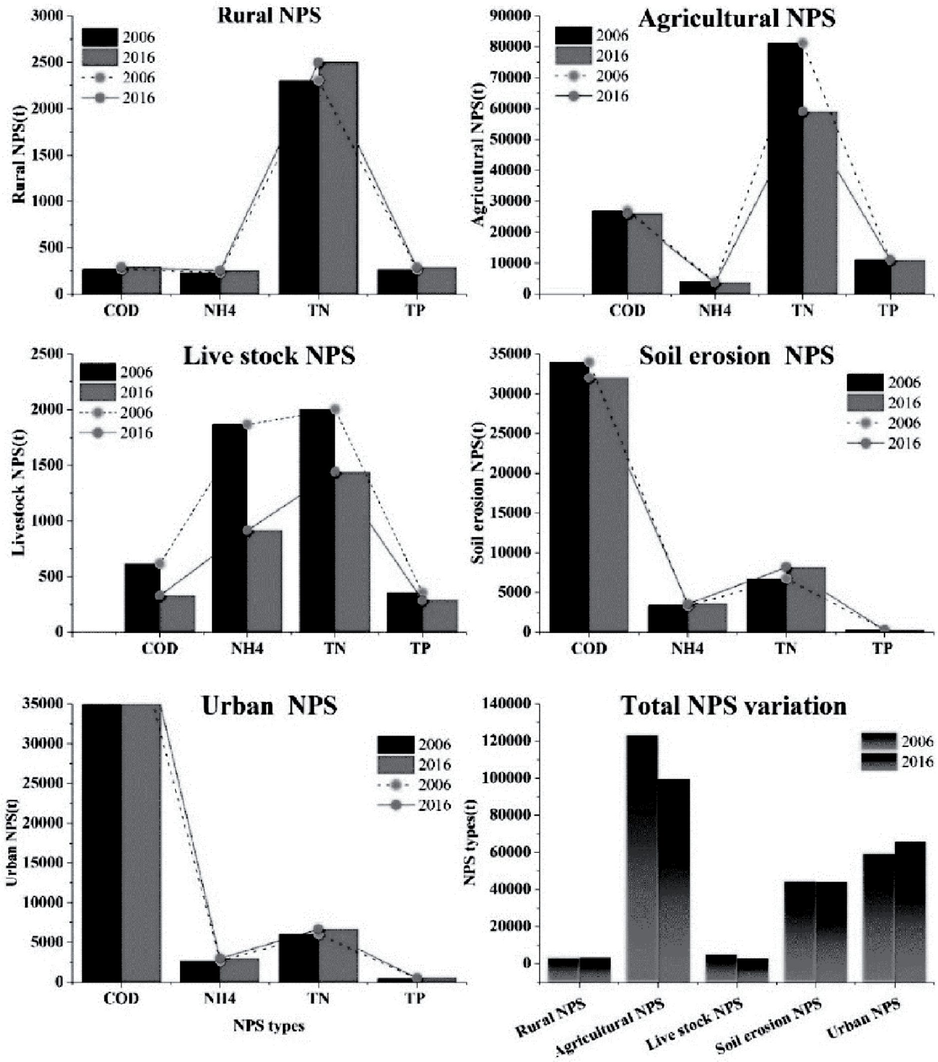

Fig. 2. Variations for the five NPSP types in Beijing from 2006 to 2016.

and 21.2%. Urban NPSP increased by 10.8% over the study period. COD was the main pollution element and reached 84.6% during the study period. TP has the most increase that reached 11.1%.

Spatial variations for the five NPSP types in Beijing from 2006 to 2016 are shown in Fig. 3. The NPSP spatial map was classified into 16 levels. Different NPSP types showed distinct differences in terms of spatial distribution; the distribution also varied from 2006 to 2016.

Rural NPSP is primarily located in the east-middle area of Beijing and covers the Changping District, Shunyi District, and Tongzhou District. From 2006 to 2016, rural NPSP in the two northern districts (Yanqing District and Miyun District) represented reverse variations, where NPSP in Yanqing decreased while NPSP in Miyun increased. In terms of agricultural NPSP, there was an area of high NPSP southeast of Beijing that included the Fangshan District, Daxing District, Shunyi District, and Tongzhou District. Agricultural NPSP did not vary drastically except in the Mentougou District. There were high levels of livestock NPSP in the south plain area and north mountain area, particularly in the Mentougou District, Fangshan District, Daxing District, Shunyi District, and Miyun District. For the study period, livestock NPSP showed drastic spatial variations. Livestock NPSP decreased in the Yanqing District but increased in the Mentougou and Shunyi districts. Soil erosion NPSP primarily occurred in the north mountain area, which included the Yanqing District, Huairou District, and Miyun District. From 2006 to 2016, soil erosion NPSP decreased, especially in the north. Urban NPSP was high in the middle region, where “old Beijing” is located. Over the study period, urban NPSP increased in the middle region and in the Huairou District.

The spatial distribution of four pollution element types are shown in Fig. 4. COD showed different spatial characteristics in 2006 than in 2016. In 2006, the area of high COD was located mainly in north districts, and the total amount was large. In 2016, the area of high COD had decreased, especially in the north. Unlike COD,

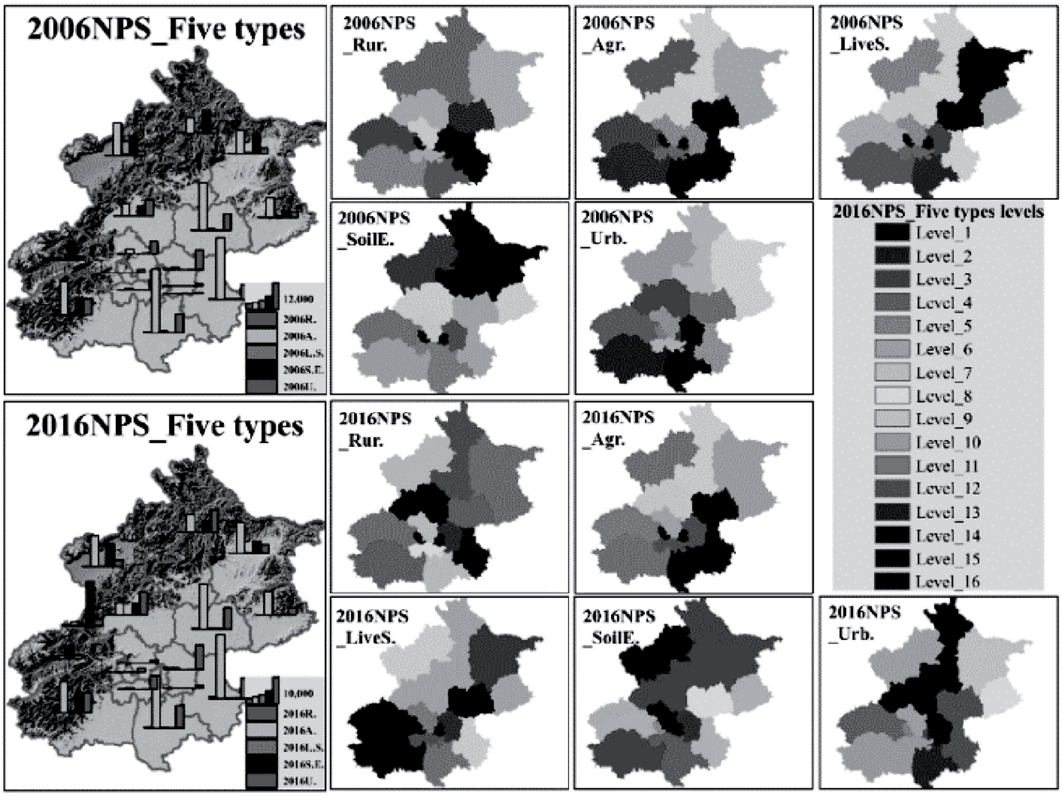

Fig. 3. Spatial variations for the five NPSP types in Beijing from 2006 to 2016.

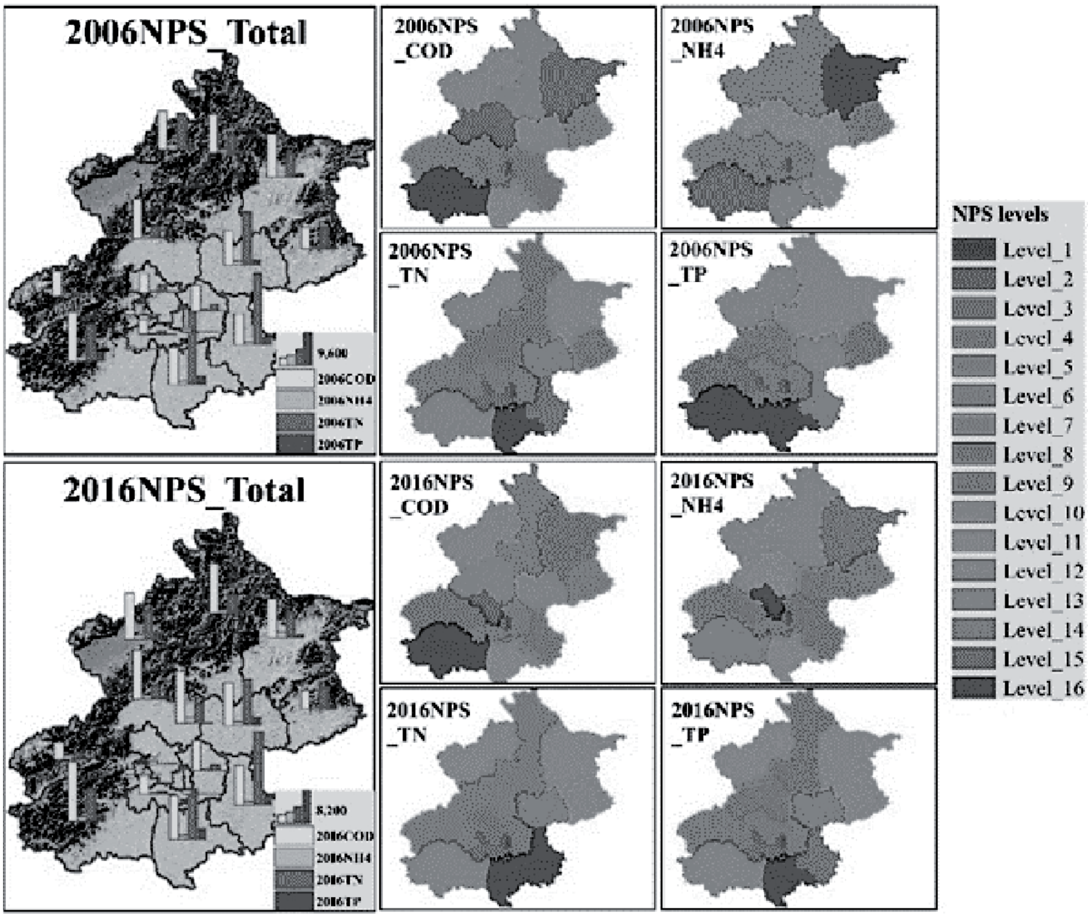

Fig. 4. Spatial variations for the four NPSP pollution elements in Beijing from 2006 to 2016.

the spatial distribution of NH_4 was similar in 2006 and 2016. Areas of high NH_4 were located in the north and in the Fangshan District. In terms of TN, there was no distinct difference between 2006 and 2016 and the area of high TN was located in the south and east. In the middle of the old urban area TN declined. TP was an important element for water quality. Areas of high TP decreased mainly in the south and in the Fangshan District.

NPSP Distribution and its Element Variations in the Different Urban Function Zones

Variations in the five NPSP types for the four urban function zones are shown in Fig. 5. Different NPSP types and characters have been presented for the four urban function zones. In the capital function core zone, only the urban total NPSP load decreased (17.3%) from 2006 to 2016. The urban functional development zone contained the five NPSP types, and total NPSP increased by 43.0%. In this zone, urban NPSP was the leading type during the study period and measured 77.3% in 2006 and 46.5% in 2016. From 2006 to 2016, rural NPSP increased by 0.9% and soil erosion NPSP increased by 22.8%, but the agricultural NPSP, livestock NPSP and urban NPSP decreased by 38.0%, 79.4% and 14.1%, respectively. In the urban development fresh zone, the total NPSP load decreased by 13.1% from 2006 to 2016. Agricultural NPSP was the primary NPSP type and measured 64.3% in 2006 and 57.2% in 2016. From 2006 to 2016, rural NPSP increased by 40.9% and urban NPSP increased by 8.4%, while agricultural NPSP, livestock NPSP and soil erosion NPSP decreased by 22.7%, 50.0% and 0.2%, respectively. In the ecological conservation development zone, the total NPSP load decreased by 14.7% over the study period. Agricultural NPSP and the soil erosion NPSP were consistently the primary pollution types.

Variations in the four NPSP pollution elements from 2006 to 2016 are shown in Fig. 6. The elements present vary between 2006 and 2016. In 2006, primary elements were COD and TN, which measured 47.7% and 41.8%, respectively. 2016 was similar to 2006 and the primary elements were also COD and TN, which measured 53.0% and 36.0%, respectively. The total amounts for NH_4, TN and TP decreased by 6.2%, 20.8% and 1.2%, respectively. COD was an exception and increased by 2.0% from 2006 to 2016.

LUCC and Population Increase Indicate that Urban Development Drives NPSP

LUCC acted as a sensitivity indicator for urban development. The variation was captured using remote sensing data from 2006 to 2016 (Fig. 7). In 2006 and

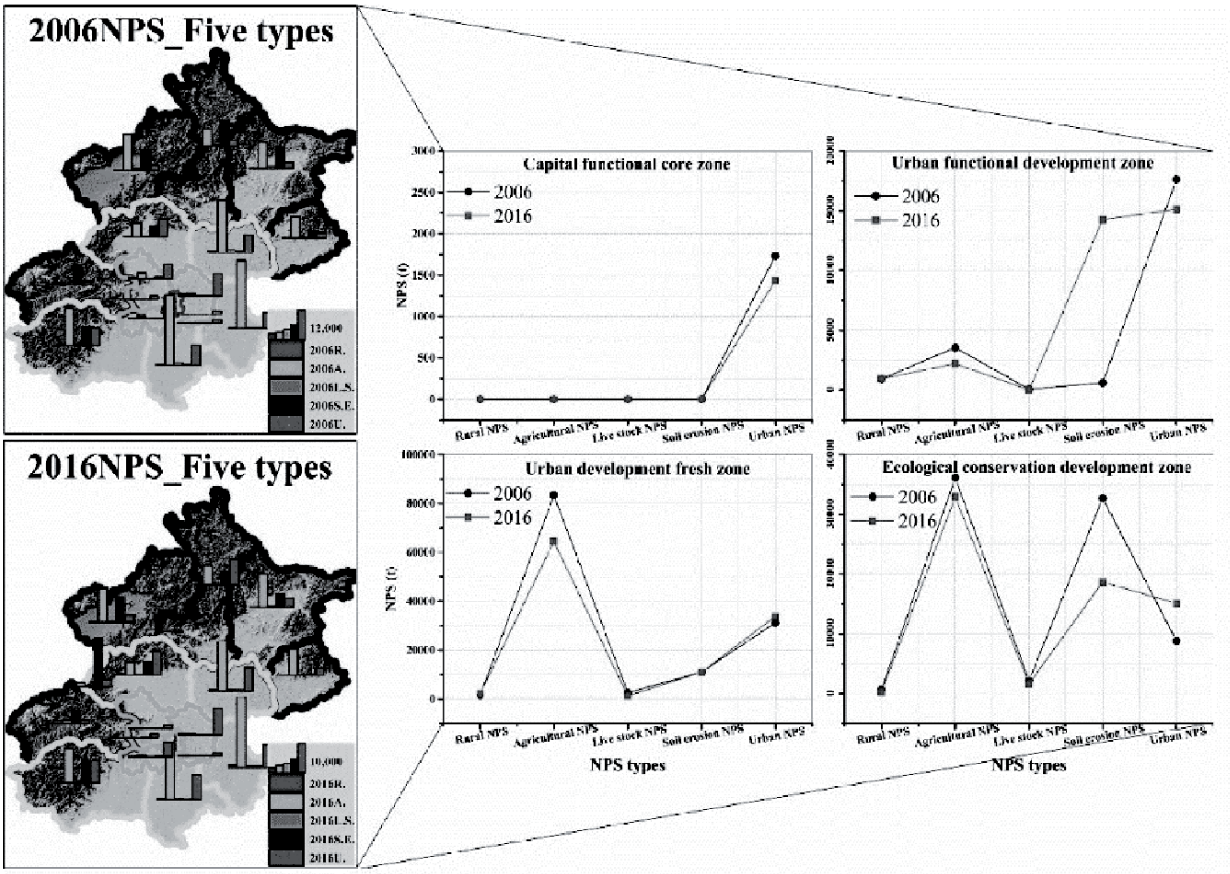

Fig. 5. Variations in the five NPSP types for the four urban function zones in Beijing from 2006 to 2016.

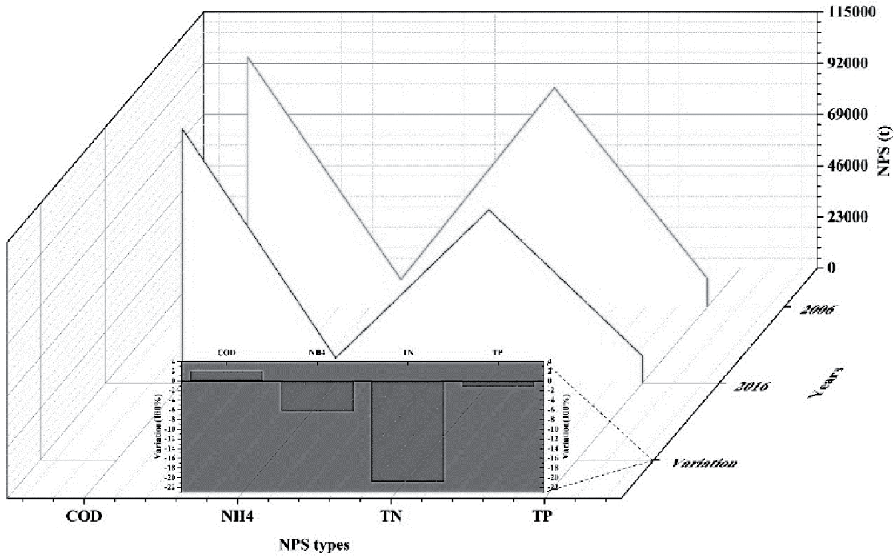

Fig. 6. Variations in four NPSP pollution elements for Beijing from 2006 to 2016.

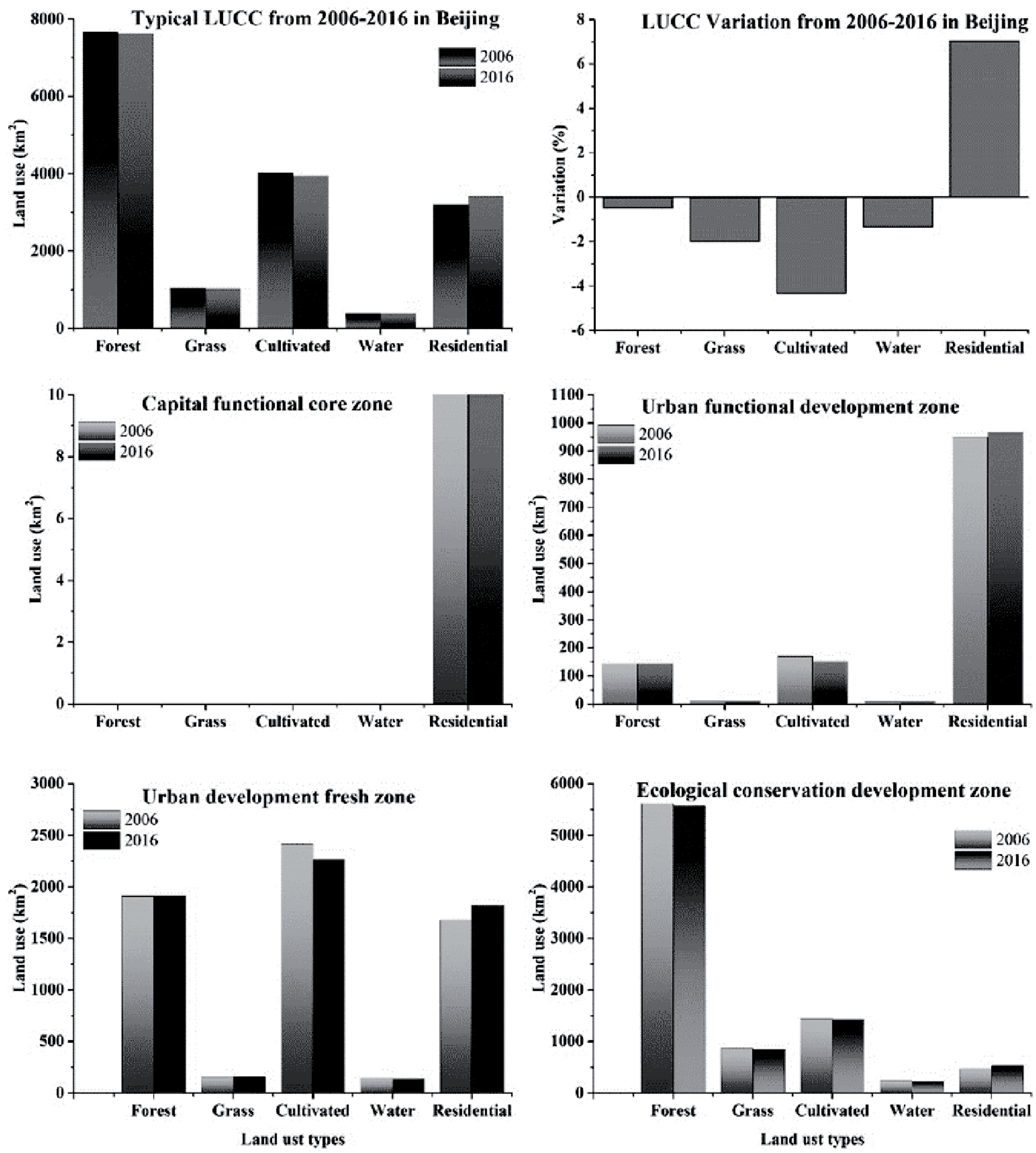

Fig. 7. Variations in LUCC for Beijing and the four zones from 2006 to 2016.

2016, the primary variation was in the residential land, which increased by 7.05% for the total Beijing area. All the other land-use types decreased. Forest land decreased by 0.48%, grassland decreased by 1.99%, cultivated land decreased by 4.33%, and the water body decreased by 1.34%. In the capital functional core zone, residential land was the only land-use type to show no change. Five land-use types exist in the urban functional development zone. Residential land alone increased by 2.0% in the two periods, while all others decreased. In the urban development fresh zone, cultivated land decreased by 6.3% but residential land increased by 8.4%. The LUCC in the ecological conservation development zone was similar to other three zones; residential land use increased by 13.6% but all others decreased.

LUCC determined the total NPSP pollution load not only in the agricultural areas but also in urban areas. LUCC influenced NPSP and amplitude both directly and indirectly. Land use associated with urban development, such as the removal of forest and grassland and replacement of pervious areas with impervious surfaces and drainage channels, changed the characteristics of the surface runoff hydrograph [35-36] and directly influenced urban NPSP contamination levels and spatial distribution patterns [37-38]. Urban NPSP has a profound influence on storm water quality due to the introduction of pollutants of physical, chemical, and biological origin, which result from anthropogenic activities [39]. The potential influence of LUCC on urban NPSP includes changes in soil characters, which are the basis for NPSP pollution release and export. In addition, NPSP remnants from previous land-use types have been released due to urban development [40-41].

Population increase and migration are significant driving forces for urban development as well as NPSP and pollution level. In this study, we surveyed total population, rural population and variations for both using the statistical yearbook (Fig. 8). Total population in Beijing during the study period increased from 11.98 million to 21.74 million, which was a 81.49% increase. In the four functional zones, total population in the capital functional core zone decreased by 5.15%, and the total population in the other three functional zones (urban functional development zone, urban development fresh zone, ecological conservation development zone) increased by 103.54%, 141.50% and 20.66%, respectively. Population in rural areas was also surveyed as an important indicator of the urbanization process. From 2006 to 2016, total rural population increased by 12.02%. Rural population occurred in the three functional zones but not the capital functional core zone. In the urban functional development zone and urban development fresh zone, the rural population increased by 0.91% and 40.86%, respectively. In the ecological conservation development zone, the rural population decreased by 41.48%.

In our research, urban NPSP and rural NPSP increased and this was related to population size

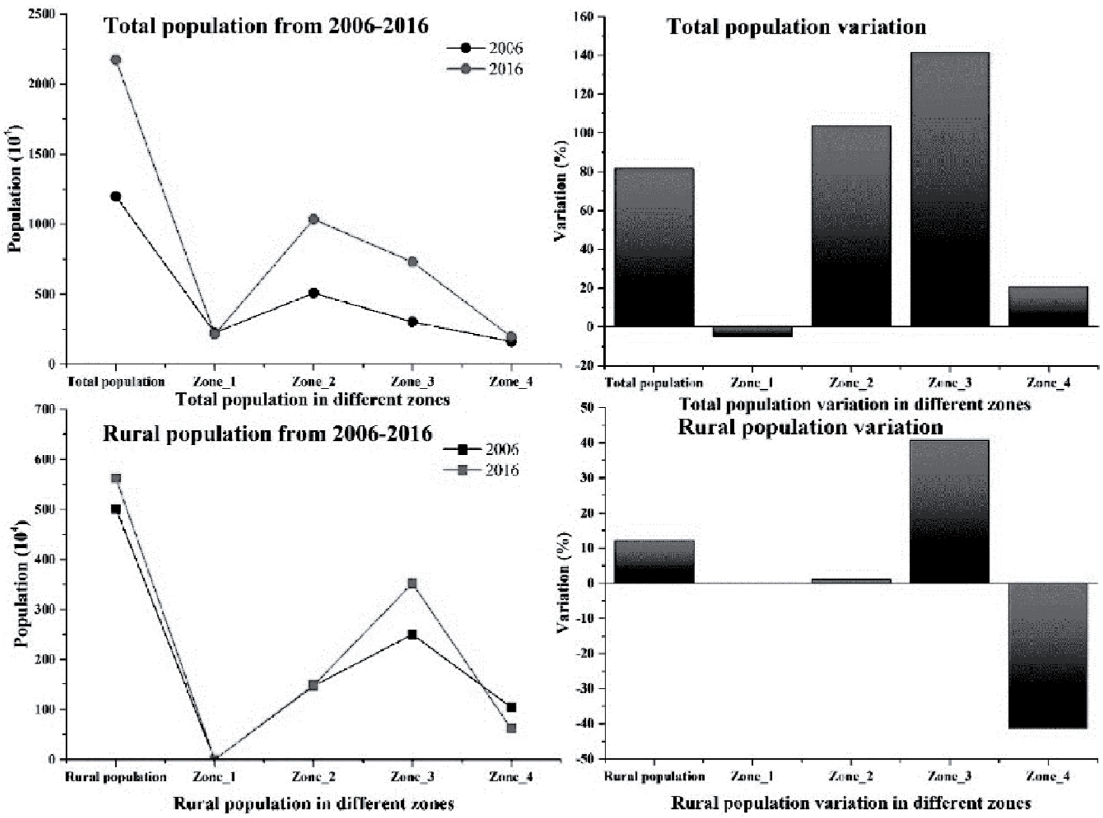

Fig. 8. Population variations for Beijing and the four zones from 2006 to 2016.

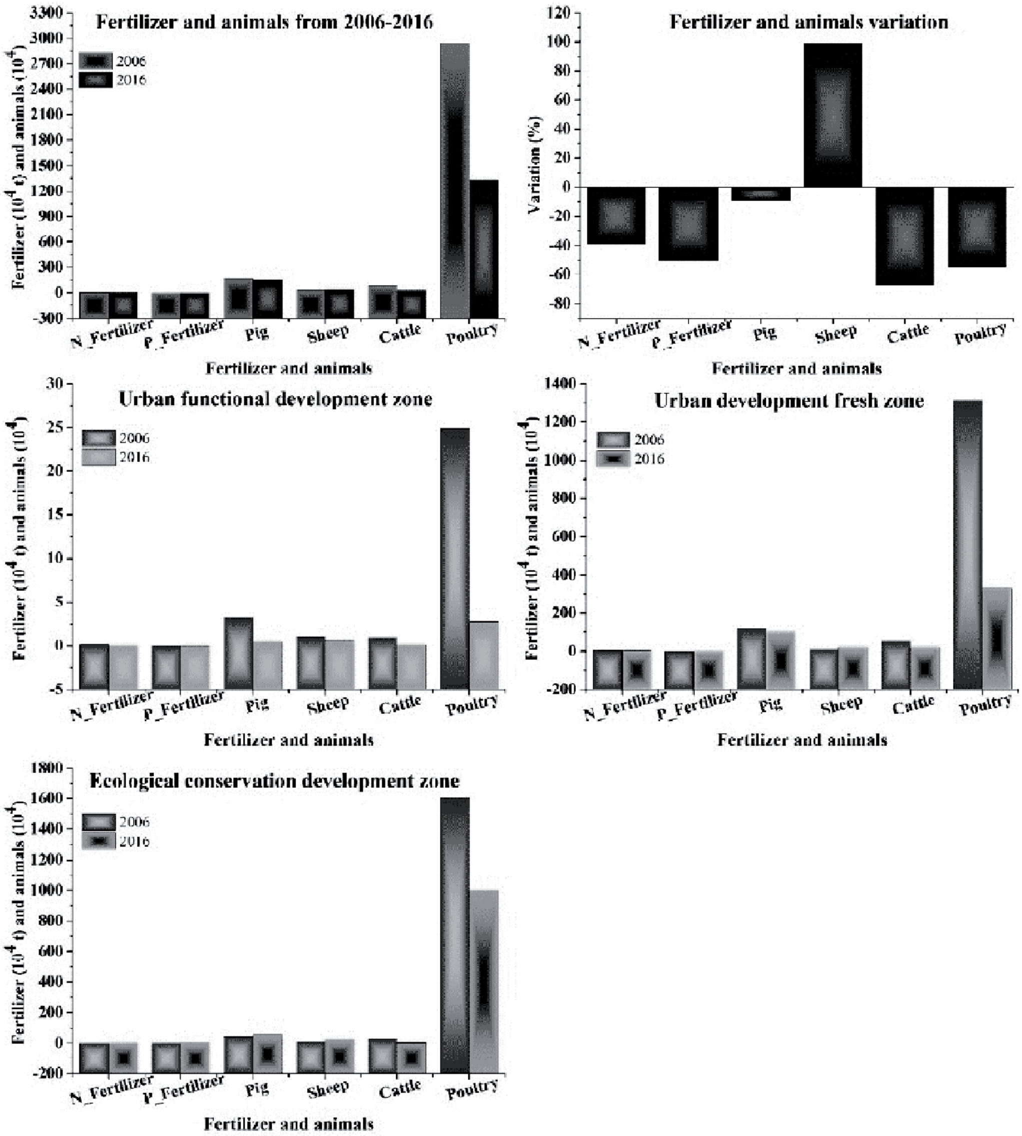

Fig. 9. Variations in agricultural production and livestock from 2006 to 2016.

(Fig. 2). In the capital functional core zone, the NPSP load decreased from 2006 to 2016 (Fig. 5). In the ecological conservation development zone, the rural NPSP decreased by 58.2% and the urban NPSP increased by 71.6% during the study period (Fig. 5). These variations in NPSP are in line with the population changes from 2006 and 2016. This indicates that population is a significant and direct driving force behind the special distribution and amount of NPSP. It is possible to explain the driving role of population from the perspective of a single person. In the pursuit of better living conditions and larger space, people have moved to developed urban and surrounding areas, and this changes the land surface for NPSP generation and transportation [42-43]. A single person is not the only unit for point source pollution but also for nonpoint source pollution [44-45]. Human activities in urban areas influence contamination elements, particularly from industrial production. This makes calculating and preventing urban NPSP more difficult [46].

Urban Development and Policy Decreases NPSP from 2006 to 2016 in Beijing

Agricultural production, including nitrogen and phosphorus fertilization and livestock production (pig, sheep, cattle, and poultry) was surveyed from 2006 to 2016 (Fig. 9). Nitrogen and phosphorus artificial fertilizer use showed similar significant declines of 38.9% and 50.4%, respectively. This was the result of the reduction in cultivated land by 4.3% from 2006 to 2016. Livestock is still an important source of food for Beijing, but the total amount has declined. The pig, cattle and poultry totals decreased by 8.76%, 67.1% and 54.8%, respectively, but sheep increased by 99.2% over the study period. Using these data, we determined that agricultural production as well as meat and poultry for Beijing declined from 2006 to 2016.

Artificial fertilization and livestock are two key NPSP sources [47-49], and they influence agricultural NPSP and livestock NPSP directly. From 2006 to 2016,

Table 2. Data used by the model.

Data type	Name	Source	Role	Spatial res.	Tem. res.	Processing method
Remote sensing data	Elevation	ASTERGDEM	Slope	30 m		CT/ENVI
	LUCC	Landsat 8	Landuse	30 m	16 d	VI/ ArcGIS
	Vegetation cover	Landsat 8	Model	30 m	1 month	RR/ENVI
	Soil type	Data base	Model	30 m		CT/ENVI
Meteorological data	Precipitation	National stations	Model	Point	1 day	SI/ArcGIS
Statistical data	Population	Statistical yearbook	Model	district	1 year	SD/ArcGIS
	Rural	Statistical yearbook	Model	district	1 year	SD/ArcGIS
	Agricultural	Statistical yearbook	Model	district	1 year	SD/ArcGIS
	Livestock	Statistical yearbook	Model	district	1 year	SD/ArcGIS
Survey data	E_h	Prior R.	Model	—	—	Check&SD
	D_{ca}	Prior R.	Model	—	—	Check&SD
	H	Prior R.	Model	—	—	Check&SD
	M	Prior R.	Model	—	—	Check&SD
	B	Prior R.	Model	—	—	Check&SD
	R_S	Prior R.	Model	—	—	Check&SD
	C	Prior R.	Model	—	—	Check&SD
	c	Prior R.	Model	—	—	Check&SD

agricultural NPSP decreased by 19.1% and livestock NPSP decreased by 38.7% (Fig. 2), even though the amount of sheep increased. Urban development, especially in the megacity, has focused on secondary industry and the service industry [50]. Therefore, agricultural development was delayed due to it being based on natural talent and that its rate of return was lower and slower than the secondary industry and the

Table 3. Important environment policies and events held in Beijing from 2006 to 2016.

No.	Year	Date	Important event and policy	Role for NPSP
1	2006	2006.8.1	First China-US strategic dialogue	–
2		2006.9.5	The 22nd world congress of law	–
3		2006.5	The six-party talks on the nuclear issue	–
4		2006.9.13	21 century forum	↓
5	2007	2007.1.31	Third sustainable development education seminar.	–
6		2007.10.3	The second session of the sixth round of the six-party talks	–
7	2008	2008.8	The 29th Olympic Games in Beijing.	↓
8		2008.9.6	Paralympic Games	↓
9		2008.10.3	2008 World Mind Sports Games	↓
10		2008.10.16	The sixth China international agricultural fair	–
11		2008.10.24	the Seventh Asia Europe Meeting	↓
12		2008.11.7	The world health organization’s first convention on traditional medicine.	↓
13		2008.11.8	China international friendship city conference.	–
14		2008.11.11	China Mining Congress and Expo	–

Table 3. Continued.

15	2009	2009.2.12	2009 Economic globalization and labor unions	–
16		2009.3	China international energy conservation and emission reduction and new energy science and technology exposition.	–
17		2009.8.17	The twenty-seventh international conference on agriculture and economics.	–
18		2009.10.9	World Media Summit	↓
19		2009.10.14	The 8th meeting of the prime ministers of the SCO member states.	–
20	2010	2010.2.25	2010 Economic globalization and labor unions	–
21		2010.5.24	The second round of china-us strategic and economic dialogue	–
22		2010.8.28	The first world war games in Beijing.	–
23		2010.8.31	The 17th Beijing international book fair.	–
24	2011	2011.4.27	2011 Economic globalization and labor unions	–
25		2011.10.5	The first Beijing professional road cycling race.	↓
26	2012	2012.4.6	The 12th China international nuclear industry exhibition.	–
27		2012.5.3	The fourth round of China-US strategic and economic dialogue	–
28		2012.5.13	The fifth trilateral summit meeting	–
29		2012.6.7	12th meeting of the council of heads of SCO member states	–
30		2012.6.7	APEC China business leaders forum	↓
31	2013		"Ecological Civilization Idea" from government	↓
32		2013.4.9	The sixth China-US Internet forum	–
33		2013.6.28	The third global think tank summit	–
34	2014	2014.6.1	International service trade fair	–
35		2014.6.21	Third world peace forum	–
36		2014.7.29	World grape conference	–
37		2014.9.16	United Nations millennium development goals (MDGS)	–
38		2014.11.10	The 22nd APEC economic leaders' meeting	↓
39	2015		"Green Development Idea" from government	↓
40		2015.7.28	Beijing world potato conference	
41		2015.8.22	IAAF world athletics championships	↓
42	2016	2016.4.28	Conference on cooperation and confidence-building measures in Asia	–
43		2016.9.10	The thirty-ninth international organization for standardization (ISO) conference	–

service industry [51-52]. Agricultural NPSP plays a significant role in the total NPSP [53], and a reduction in agricultural NPSP can significantly improve environmental quality – particularly for water bodies in Beijing.

Continuous urban development and expansion have led to the transition of the megacity, and the service industry has flourished in the process. At the same time, the megacity has become an experimental area for new national policies, especially environmental policies spearheaded by a country. Between 2006 and 2016, there were 43 important events and policies implemented in Beijing (Table 3). These events included major sporting events, such as the 29th Olympic Games, and international meetings and forums, such as the APEC China business leaders forum. Important environmental policies include "Ecological Civilization Idea" and "Green Development Idea." These events and policies were classified into two types: common events and NPSP reduction events; policies are represented by a green arrow (Table 3).

These important events and policies have had a direct and immediate influence on NPSP load reductions in Beijing. In order to improve environmental quality, urban planning and management were utilized for these meetings and sporting events. For example, in preparation for the 29th Olympic Games, work was done in Beijing to enhance environmental quality (e.g., rain, dirt separation), improve the urban living environment (e.g., shantytowns transformation), and to promote the city image [54-55]. These major events and policies drove urban development in the short-term and changed land surface conditions as well as NPSP loading [56]. The characteristics of NPSP loading and prevention in a megacity are very different from NPSP pollution in an agricultural watershed [57]. NPSP in a megacity requires more attention in terms of the role of environmental policies.

Conclusions

This work examined variations in and the spatial distribution of five NPSP types (rural NPSP, agricultural NPSP, livestock NPSP, soil erosion NPSP and urban NPSP) and four pollution elements (COD, NH_4, TN and TP). Our research focused on Beijing, which represented a typical developing megacity, from 2006 to 2016. For our calculations, we used a model set of export coefficients and statistical models. The NPSP load and spatial distribution were also analyzed in the four city functional zones.

Our results indicate that the total NPSP amount in a single year varied from 234,700 t in 2006 to 215,709 t in 2016, representing a decrease of 8.1%. For the five NPSP types, agricultural NPSP was the primary NPSP source and measured 46.2% in 2016. Agricultural NPSP, livestock NPSP and soil erosion NPSP decreased by 19.1%, 38.7%, and 0.8%, respectively. Urban NPSP and rural NPSP increased by 10.8% and 8.5%, respectively. The spatial distribution of the five NPSP types did not demonstrate significant variations from 2006 to 2016, except in the case of urban NPSP. In the four functional zones, urban NPSP was the only type in the capital function core zone where the total NPSP load decreased (by 17.3%) from 2006 to 2016. In the urban functional development zone, the total NPSP increased by about 43.0%, in the urban development fresh zone, the total NPSP load decreased by 13.1%, and in the ecological conservation development zone, the total NPSP load decreased by 14.7%. The urban functional development zone was key to preventing NPSP in a developing megacity.

The driving forces behinds the NPSP variation in the megacity included urban development, population increase and migration, as well as policy and the role of urban transformation. Urban development led to land-use and land-cover changes and this influenced the NPSP load in the megacity. Population increase and migration had a direct impact on urban NPSP and rural NPSP at the megacity scale by increasing P loading into the environment. Urban development reduced agricultural production and the related NPSP loading. Policy and the role of urban transformation caused the NPSP load to decrease in the short-term in the megacity. Our research analyzed variations in multi-source NPSP types in the megacity on a long-term timescale and addressed the question of what drives these variations. This information not only has new implications for the law of NPSP on a megacity scale, but also helps managers make better policies regarding urban planning and NPSP prevention in a developing megacity.

Acknowledgements

We acknowledge all of the editors and reviewers for their valuable advices. The authors would also like to thank the financial support from the National Natural Science Foundation of China (Grant Nos. 41801334, U1812401, U1603241), the financial support from the China Postdoctoral Science Foundation (2017M620663), the Fundamental Research Funds for the Central Universities (2017NT11), the National Key Project for R&D (2018YFC0407900), and National Young Scientist Natural Science Foundation of China (41601569). We thank Kara Bogus for editing the English text of a draft of this manuscript.

Conflict of Interest

The authors declare no conflict of interest.

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