
The Applications of ‘N Offset’ Mechanism in the Evaluation of Reactive Nitrogen Emissions Reduction in a Typical China’s Urban Agglomeration

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Abstract: The rapid development of urbanization, resulting in direct and indirect emissions of anthropogenic reactive nitrogen to environment during nitrogen consumption, had brought the huge ecological pressure and serious environmental pollution. Took a typical China’s urban agglomeration (Beijing-Tianjin-Hebei agglomeration) as example, this study constructed quantitative analysis of reactive nitrogen emissions and an evaluation index for annual reactive nitrogen removal efficiency of this region by employing data envelopment analysis. After that, this study attempted to put forward reactive nitrogen reduction countermeasures based on ‘N offset’ mechanism for the collaborative development. The results showed that, during urbanization from 2004-2014, the total reactive nitrogen emissions by Beijing-Tianjin-Hebei agglomeration presented slightly decreased with fluctuation. Hebei province was the main contributor to nitrogen emission, occupying 79-84% and 74-79% of nitrogen loss to atmosphere and hydrosphere. The main sources of regional emissions were agricultural activities primarily, and then turned to industrial activities and residential livelihood. The differences existed in the impacts of urbanization on reactive nitrogen emission intensity of each region. The annual emission intensity of this agglomeration was 5.8 t N/km². Beijing city owned the highest of emission reduction efficiency. The reduction in the emissions intensity of Hebei province and the improvement in emission reduction efficiency of Tianjin city were supposed to be the keys for overall low-nitrogen urbanization within agglomeration. The nitrogen-reduction countermeasures accompanied by corresponding pecuniary compensation, basing on collaborative ‘N offset’ mechanism, would contribute to the reciprocity among Beijing-Tianjin-Hebei agglomeration towards sustainable development.

Keywords: Urbanization, Reactive Nitrogen, Data Envelopment Analysis, Nitrogen Offset, Beijing-Tianjin-Hebei Agglomeration

1. Introduction

With rapid global urbanization, anthropogenic activities have strong impacts on the biogeochemical cycle of nutrient element nitrogen (N). As the heterotrophic ecosystem dominated by human, urban ecosystems need to consume exotic nitrogen to maintain the development and production of system as well as meeting the human needs, inevitably bring serious environmental problems. The anthropogenic consumption of N may directly and indirectly lead to emissions of reactive N [Nr], which generally includes all

reactive N atoms contained in organic N, ammonia (NH₃), oxynitride (NO_x), nitrous oxide (N₂O), nitrate and amide, that load groundwater and surface water via leaching, erosion, and runoff. The excessive release of Nr induces a series of global and regional environmental problems with nitrogen cascade [1], which is regarded as the third most important global environmental problem after biodiversity loss and global warming [2]. Thus, it is important to understand the driving forces of anthropogenic impacts on Nr cycling disturbance during urbanization. As one of the countries with rapid urbanization in the world, China experienced an

unprecedented growth in urban population from 17.7% in 1978 with its 'Reform and Opening' policy implement to 54.8% in 2014, and it is predicted to reach 60% in 2020 [3]. This dramatic growth in urbanization would therefore boost Nr agricultural and industrial activities in China, which was the largest anthropogenic Nr producer in the world [4] with the livestock and crop farming being the main contributors [5]. The improvements in the residential settlement and industrialization contributed to the increasing of urban Nr releasing [6], and also drove the intense Nr productions through agricultural and industrial activities in suburban region to meet the needs of urban regions, resulting in the further growth of Nr loads to environment [7] that threatened the whole region during urbanization with nitrogen pollution including the acid rain, eutrophication, air pollution, and biodiversity reduction [8]. Therefore, it is essential to estimate the Nr emissions to environment during urbanization before launching the nitrogen-reduction countermeasures. As statistical data for calculating Nr were often reported using different units of measurement, it is necessary to convert all the amounts involved into a total net mass of N in units of t (Ton), Gg (Gigagram), or Tg (Teragram) ($1\text{ t}=10^6\text{ g}$; $1\text{ Gg}=10^9\text{ g}$; $1\text{ Tg}=10^{12}\text{ g}$) [9], which could quantify the amount of total Nr emission with integrating multi-source non-point Nr loss.

To date, most studies related to Nr loss evaluation had addressed the anthropogenic Nr loss and their negative impacts through the estimation of urban Nr burden [10-11], or the calculation of urban nitrogen footprint [12-13]. However, few studies had addressed the Nr emissions from multi-sources within urban regions due to limitation of obscure boundary and data availability for Nr emissions estimations [10-11]. In China, the studies related to urban Nr evaluation usually adopted the 'nitrogen footprint' indicator to estimate upstream and downstream nitrogen loss during urbanization, but this merely indicated the level of nitrogen loss caused by urban food and energy consumption, and failed to respectively reveal the environmental impacts of Nr emissions on atmosphere, hydrosphere and geosphere [13], which was important for Nr source apportionment to help government to target the main urban Nr sources. Moreover, currently there still lacked the universal model for the evaluation of Nr removal efficiency in the urban region that could assess the progress in the reduction of Nr emissions by government. All these were important for government to launch relevant Nr reduction countermeasures to mitigate local nitrogen pollution. Generally, agricultural activities were the main sources of Nr loss in China, however, with rapid urbanization, the main sources of N consumption and accompany Nr emissions were then turned to industrial activities and residential livelihood driven by increase of gross domestic production (GDP) [11], which mainly occurred in urban agglomeration including several sub-regions with different urbanization levels. Here, This study takes Beijing-Tianjin-Hebei agglomeration in China as example and evaluates the Nr removal efficiency by regional government by employing data envelopment analysis [14] based on the

results of mutli-source Nr emissions estimation, aiming at provide suggestions for the reciprocity among Beijing-Tianjin-Hebei agglomeration with urbanization in terms of Nr mitigation.

2. Methodology

2.1. Study Area

The Beijing-Tianjin-Hebei agglomeration ($36^{\circ}01'—42^{\circ}37' \text{ N}$, $113^{\circ}04'—119^{\circ}53' \text{ E}$) with the area of $21.44 \times 10^4 \text{ km}^2$, is at the northern tip of the North China Plain, it includes Beijing city, Tianjin city and Hebei province. The population of this agglomeration is not evenly distributed and the hotspots of population distribution mainly located in the two municipalities, and the Shijiazhuang and Xingtai city in the southern Hebei province (Figure 1). The Beijing-Tianjin-Hebei agglomeration is the third largest integrated development region in the China, secondary to the agglomerations of Yangtze river delta and the Pearl river delta, but its second industry proportion is higher compared with other two agglomerations, resulting in serve ecological pressures on regional ecosystems with the growth of pollutants emissions [15]. In 2014, the urbanization rates of Beijing and Tianjin cities were over 80% while the rate of Hebei province still below 50% at the same time. As the municipalities that are embedded in the Hebei province, Beijing and Tianjin cities had the priorities of economic development and urbanization, this resulted in more population migration to these two cities, and also increased the risks that Hebei province were suffering from environment pollution since Hebei province always played the role of granary in the Beijing-Tianjin-Hebei agglomeration (93.3% crop, 92.1% vegetable, 84.5% meat and 79.2% milk were produced in Hebei in 2014) [16]. Thus, the rise demand for food production increased the N consumption and therefore caused to more Nr releasing to surrounding environment. Moreover, more heavy industries moved from Beijing and Tianjin to Hebei province during urbanization due to limitation of land resource and severe pollutant control in these two cities, resulting in about 66% energy consumption in Hebei province. This symbiotic development mode with obvious differences in sub-region tended to significantly improve the urbanization of two municipalities, and also brought larger ecological pressures on the sustainable development of Hebei province, inevitably resulting in regional environmental problems contributed by the growth of Nr load in Hebei province that threaten the whole Beijing-Tianjin-Hebei agglomeration such as widespread persistent haze and groundwater pollution. To address this problem, the Chinese government carried out a series of national policies that emphasized the regional atmospheric and water environmental problems was the key to the coordinated development of Beijing-Tianjin-Hebei agglomeration.

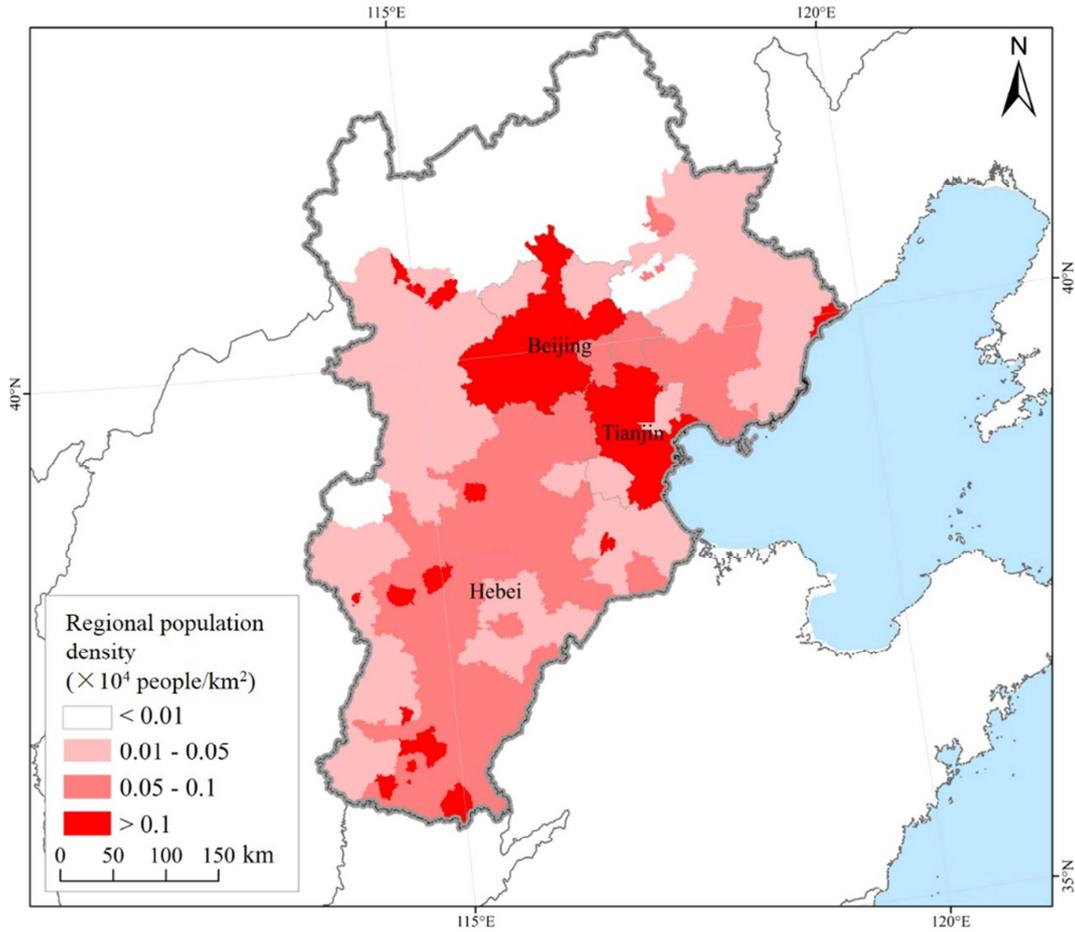


Figure 1. Zone map of Beijing-Tianjin-Hebei agglomeration as well as population distribution.

2.2. Method

2.2.1. Estimation of Agricultural Nr Emissions

During agricultural production in China, ammonia (NH_3) volatilization from livestock farming and synthetic fertilizer application were the major contributors to agricultural Nr emissions to the air [18]. Besides, as one of important

greenhouse gases, nitrous oxide (N_2O) would be produced from fertilizer application. Nitrogen dioxide (NO_2) emissions would be neglected during overall Nr estimation due to its limited production from agricultural activities in China [4]. Therefore, the agricultural Nr emissions to air could be estimated by Formula 1 as follows:

$$A_{air}^i = V_{liv}^i + V_{fer}^i + D_{fer}^i = \sum_{j=1}^n M_j^i \times EF_{liv} + (Fer_n^i \times NC_n \times EF_{fer} + Fer_c^i \times NC_c \times EF_{fer}) + (Fer_n^i \times NC_n \times DE_{fer} + Fer_c^i \times NC_c \times DE_{fer}) \quad (1)$$

Where A_{air} denoting gaseous Nr emissions from agricultural activities with i denotes specific year. V_{liv} and V_{fer} indicate the annual Nr losses resulting from NH_3 volatilization from livestock farming and synthetic fertilizers (nitrogenous and compound fertilizer), and D_{fer} represents the annual Nr loss from denitrification. M_j denotes the annual rearing capita of livestock species j and EF_{liv} represents the emission factors for annual NH_3 volatilization (Table 1). Livestock species refers

to the major NH_3 producers (cattle, horses, donkeys, mules, pigs, and sheep) during grazing or husbandry. Fer_n and Fer_c are the annual amount of nitrogenous and compound fertilizer applications, respectively. The NC_n (46.0%) and NC_c (12.8%) are the average nitrogen content of these fertilizers [20], with EF_{fer} (16.0%) and DE_{fer} (0.4%) representing the loss rates of fertilizer N via NH_3 volatilization and denitrification to N_2O [19, 21].

Table 1. Reactive nitrogen emission factors and nitrogen excretion of large livestock farming [19].

Large livestock	NH_3 volatilization ($\text{kg N} \cdot \text{cap}^{-1} \cdot \text{a}^{-1}$)	Total excretion ($\text{kg N} \cdot \text{cap}^{-1} \cdot \text{a}^{-1}$)
Beef	45.87	18.6
Horse	68.64	18.6
Donkey	68.64	18.6
Mule	68.64	18.6
Sheep	11.23	4.18
Pig	4.87	2.33

In China, the intense agricultural activities caused more riverine Nr to be added into the aquatic ecosystem by direct discharge or such indirect routes as irrigation water loss, rainfall-runoff, and leaching [22], and livestock farming and

cropland fertilization were also supposed to be as the largest source for groundwater N accumulation via Nr leakage [23], the agricultural Nr emissions to water could be estimated by Formula 2 as follows:

$$A_l^i = L_{liv}^i + L_{fer}^i = \sum_{j=1}^n M_j^i \times P_{exc} \times (1 - P_r) \times L_{exc} + (Fer_n^i \times NC_n \times L_{lea} + Fer_c^i \times NC_c \times L_{lea}) \quad (2)$$

where A_l represents the amount of Nr releasing via leaching during agricultural activities. L_{liv} and L_{fer} denote the total Nr loss via leaching from livestock farming and fertilizer applications. P_{exc} represents the livestock N excretion rates (Table 1), and P_r is the overall excretion recycled ratio in China (40%). L_{exc} and L_{lea} represent the loss rates of animal excretion (5.0%) and fertilizers (0.5%) through leaching [19].

Given the lack of official statistical data concerning agricultural wastewater discharge, this part of riverine Nr releasing was estimated by considering fertilizer application in China in alliance with specific Nr runoff loss coefficients, since it was common practice to estimate Nr loss via runoff as a fraction of the applied fertilizers [24].

$$A_w^i = (Fer_n^i \times NC_n \times EF_{wat} + Fer_c^i \times NC_c \times EF_{wat}) \quad (3)$$

where A_w represents the amount of Nr embedded in the wastewater via irrigation runoff during agricultural activities and EF_{wat} is the corresponding loss rate (5.2%) [19]. Therefore, the agricultural Nr emissions to water could be estimated by the sum of A_l and A_w .

2.2.2. Estimation of Industrial and Residential Nr Emissions

The people urbanization and regional industrialization usually were driving the growth of Nr load to environment. Widespread industrialization directly spurred NO_x emissions after energy consumption, and indirectly caused to industrial wastewater discharging to water environment, even after wastewater treatment. The industrial Nr emissions to environment could be estimated by Formula 4 and 5 as follows:

$$I_{air}^i = M_I \times NC_{NOX} \quad (4)$$

$$I_{water}^i = W_I \times NC_w \div P_{NH} \quad (5)$$

Where I_{air} and I_{water} represent the amounts of Nr loss embodied in industrial NO_x emissions and industrial ammonia nitrogen discharging. M_I presents the annual emissions of industrial NO_x and NC_{NOX} is the nitrogen content of NO_x , on account of the NO_2 atomic composition (presuming NO_x as NO_2 due to the instability of NO) [25]. W_I presents the annual industrial ammonia nitrogen discharging since ammonia nitrogen was the only component of riverine N that is regularly monitored in China [22], and NC_w is the nitrogen content of ammonia nitrogen. P_{NH} presents the overall percentage (70%) of ammonia nitrogen to total nitrogen in untreated wastewater in China [26].

Similarly, the residential Nr emissions to environment

could be estimated by Formula 6 and 7 as follows:

$$R_{air}^i = M_R \times NC_{NOX} \quad (6)$$

$$R_{water}^i = W_R \times NC_w \div P_{NH} \quad (7)$$

Where R_{air} and R_{water} represent the amounts of Nr loss embodied in residential NO_x emissions and residential ammonia nitrogen discharging. M_R presents the annual emissions of residential NO_x and W_R presents the annual residential ammonia nitrogen discharging. The estimations of R_{air} and R_{water} were similar to those of I_{air} and I_{water} .

2.2.3. Evaluation of Nr Removal Efficiency

Given that the development of city consumes element N and results in Nr emissions to environment, it is essential to evaluate the Nr removal efficiency of that city to assess the progress in Nr mitigation by local governmental forces with urbanization. Data envelopment analysis (DEA), which was improved for input-output evaluation since it was proposed by Charnes in 1978 [27], was recently used in ecological efficiency evaluation in China [28]. In this study, DEA was used to measure the Nr removal efficiency of Beijing and Tianjin cities, as well as Hebei province. This model is a linear programming-based technique for evaluating the relative efficiency of decision-making unit (DMU) with the same resource consumption (material input) to produce the same output, accompanied by some undesirable outputs such as gaseous and aquatic pollutants emissions [29] that are need to be minimized during eco-efficiency assessment. The recent studies focusing on the assessment of urban material metabolism in China had both regarded Nr discharge as one of the undesirable outputs [30-31]. To focus on the Nr removal efficiency of Beijing, Tianjin and Hebei from 2004 to 2014, the application of DEA was conducted as suggested by Liu et al. [31], and the evaluation accounting for variable returns to scale (VRS) situation was carried out base on the DEAP version 2.1 program. In the situation, considering DMUs with time series data (years) and assuming that environmental technology for pollutant removal did not vary across study period to enable a comparison among DMUs based on the extent to which inputs were used efficiently in the output production, therefore, the DEA model could be used with time series data. The inputs and outputs were considered in the model for each DMU for a specific year. The input items included the water consumption, energy consumption, land exploration (land resource consumption), and environmental investment (financial resource consumption) (Table 2), while

Nr emission was recognized as the only output item for the propose of this study [14]. Although all the input and output items were used with different dimensions, the optimal efficiency of DMUs would not affected by the different dimensions of selected input and output items [32]. During the evaluation, the undesirable Nr outputs were treated as normal outputs after taking their reciprocals to match the model application [29]. The output slack would occur only if it was possible to increase the amount of output when keeping the same input amounts [33]. Therefore, the DMU could be

assumed to be efficient (value=1) if the output could be increased further on the premise of current maximum input; otherwise, the DMU remained inefficient (value<1) with output slack (or input slack). This meant that, in an efficient year in the current study, the Nr output (Nr emissions) could not be reduced further based on the realistic inputs of financial investment, water, energy and land. Otherwise, in an inefficient year, the Nr output could be reduced further on account of current inputs, the Nr emissions in the research area were failed to be minimized.

Table 2. Summary of input indicators of Beijing-Tianjin-Hebei agglomeration [34-35].

Input item	Beijing			Tianjin			Hebei		
	Mean	Minimum	Maximum	Mean	Minimum	Maximum	Mean	Minimum	Maximum
Environmental investment ($\times 10^8$ yuan)	246	65	624	118	41	279	309	91	624
Water consumption ($\times 10^8$ t)	25	22	29	11	9	13	52	49	55
Energy consumption ($\times 10^4$ t SCE)	6001	5050	6831	5633	3392	7955	25324	17348	30250
Land exploration (km ²)	46	14	53	49	17	70	35	20	49

2.2.4. Data Sources

The statistical data covering the field of economy, environment, agriculture and energy that used in this study were collected from China Statistical Yearbooks (2005-2015) [34], China Environmental Statistical Yearbooks (2005-2015) [35], Beijing Statistical Yearbooks (2005-2015) [36], Tianjin Statistical Yearbooks (2005-2015) [37], Hebei Statistical Yearbooks [16] and relevant regional environmental status bulletins. Considering the limitations of some statistical data, the annual amounts of industrial and residential NO_x emissions in the year 2004 and 2005 were retrieved from those in the 2006, the annual amount of land exploration by Beijing city during 2005—2009 were retrieved from those in the 2004, while the land exploration by Tianjin from 2004—2005 were retrieved from those in the 2006. The multisource activity data and corresponding coefficients for Nr emissions estimation were collected from recent literature and survey data.

3. Results and Discussion

3.1. The Estimation of Nr Emissions by Beijing-Tianjin-Hebei Agglomeration

Using the equations detailed above, Nr emissions by Beijing city, Tianjin city and Hebei province were determined from 2004—2014 (Table 2). Obviously, Hebei province was the main contributor of both gaseous and aquatic Nr emissions within the Beijing-Tianjin-Hebei agglomeration, with the percentages of 79%~84% and 74%~79%, respectively. Agricultural activities were the main source of gaseous Nr emissions in this region before 2010, occupying 50%~55%, but the industrial activities turned to be the main source since 2011 with the percentage of 40%~45%. As the two engines of economic development in the agglomeration, the gaseous Nr emissions by Beijing and Tianjin cities were similar before 2007, however, the Nr emissions by Tianjin then increased and exceeded over those by Beijing until 2011, with significant rise in industrial Nr emissions due to widespread establishment of heavy industries. By 2014, the growth rate of

industrial production of Tianjin was more than 9 folds those of Beijing and Hebei [16]. The level of total gaseous Nr emissions by Tianjin in 2014 was higher than the level in 2004, also was higher than the level by Beijing in 2014. The level of total gaseous Nr emissions by Beijing remained relevantly stable during the study period with similar percentages of industrial and residential Nr emissions, which was different from the cases of Tianjin and Hebei. What should be note that, since the 12th Five-Year Plan in 2011 (the 12th Five-Year Plan for Economic and Social Development of the People's Republic of China), the reduction of nitrogen oxide emission was stated by the country as the obligatory target for the following national economic development. Therefore, the industrial gaseous Nr emissions by the whole agglomeration decreased significantly from 2011, which contributed to overall reduction of Nr emissions. In general, the Nr emissions to air by the region were decreased by 4% in 2014, compared with those in 2004.

Different from the situation of gaseous Nr emissions, agricultural activities were the main source of aquatic Nr emissions in this region before 2008, occupying 41%~42%, but the residential activities then turned to be the main source with the percentage of 43%~51%, and the increased trend was continuing (Table 2). In 2004, the level of emissions by Beijing was similar to Tianjin, however, the emissions by Tianjin were increasing with fluctuation while Beijing's emissions presented decreasing steadily. Residential livelihood was the main source of emissions in these two cities, the lever of total Nr emissions by them were lower than that by Hebei province, but the emissions per capita of Beijing (0.7 kg N) and Tianjin (1.0 kg N) were both over that of Hebei (0.6 kg N), the main Nr source of which still was agricultural activity. The proportion of total water resources in Hebei province occupied 77% of agglomeration, and most of aquatic Nr emissions occurred in Hebei province, therefore, the aquatic environment of agglomeration was threatened by the risk of N pollution. As mentioned above, the ecosystem of Hebei province received majority of gaseous and aquatic Nr emissions during coordinated urbanization of whole region.

Some previous studies concluded that the environmental carrying capacity of Beijing was supposed to be strongest within the agglomeration while Hebei’s capacity was weakest [17]. Thus, compared with two municipalities, Hebei province

was more vulnerable to the threats of N pollution, resulting in regional environmental problems including widespread persistent haze and groundwater pollution that currently sprawled within the agglomeration.

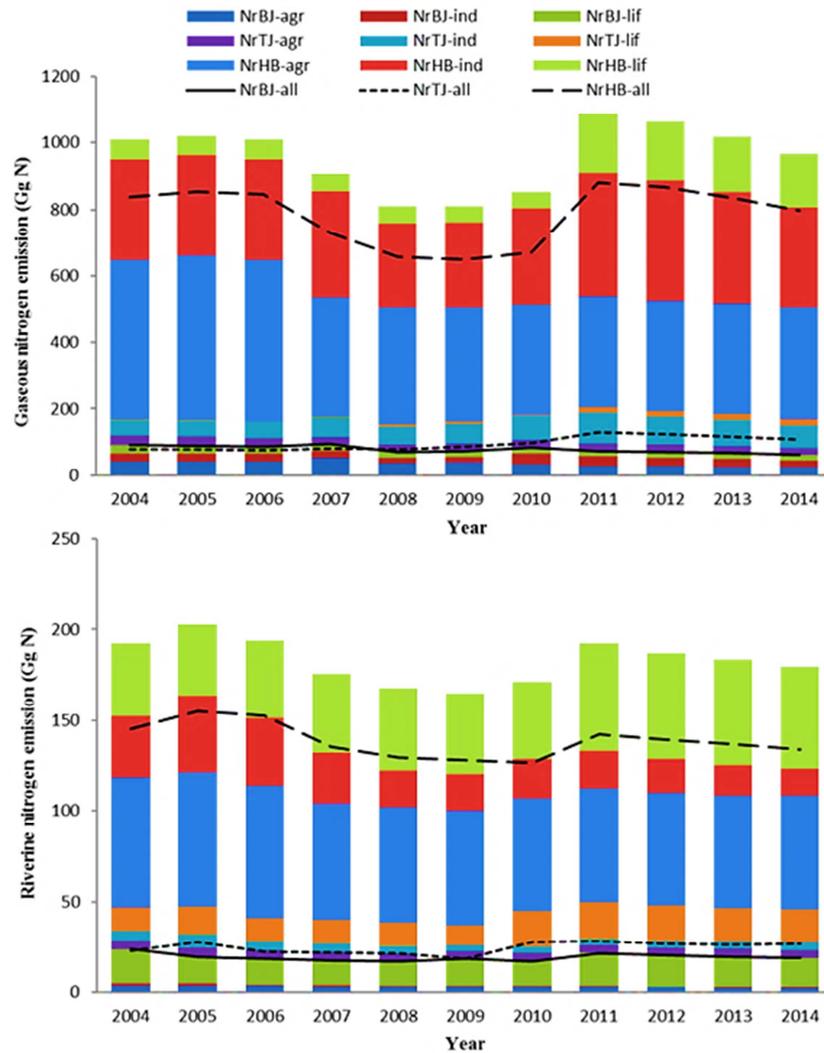


Figure 2. Multisource reactive nitrogen emissions of Beijing-Tianjin-Hebei agglomeration from 2004-2014.

$N_{rBJ-agr}$ referred to agricultural reactive nitrogen emission in Beijing; $N_{rBJ-ind}$ referred to industrial reactive nitrogen emission in Beijing; $N_{rBJ-lif}$ referred to residential reactive nitrogen emission in Beijing; $N_{rTJ-agr}$ referred to agricultural reactive nitrogen emission in Tianjin; $N_{rTJ-ind}$ referred to industrial reactive nitrogen emission in Tianjin; $N_{rTJ-lif}$ referred to residential reactive nitrogen emission in Tianjin; $N_{rHB-agr}$ referred to agricultural reactive nitrogen emission in Hebei; $N_{rHB-ind}$ referred to industrial reactive nitrogen emission in Hebei; $N_{rHB-lif}$ referred to residential reactive nitrogen emission in Hebei; $N_{rBJ-all}$ referred to total reactive nitrogen emission in Beijing; $N_{rTJ-all}$ referred to total reactive nitrogen emission in Tianjin; $N_{rHB-all}$ referred to total reactive nitrogen emission in Hebei.

During 2004—2014, the urbanization of the whole agglomeration was accelerated, especially in the Hebei province (Table 3). Although the level of urbanization in Hebei

province was merely half of levels in Beijing and Tianjin cities, annual average Nr emission by Hebei (0.92 Tg N) was more than 4 times the sum of latters (0.22 Tg N) (Table 2). The level of urbanization in Tianjin city was lower than Beijing city, but its growth rate was over that of Beijing, especially from 2007—2008. During the study period, the Nr emission intensity per unit area by Tianjin ($10.7 \text{ t N}\cdot\text{km}^{-2}$) was higher than those by Beijing ($5.8 \text{ t N}\cdot\text{km}^{-2}$) and Hebei ($4.9 \text{ t N}\cdot\text{km}^{-2}$), indicating that Tianjin played the role of ‘engine’ in the regional Nr emissions by agglomeration. Beijing, with high level of urbanization, decreased its Nr emission intensity and tended to be similar to the lower level of Hebei’s Nr emission intensity with continue urbanization, while Hebei, with low level of urbanization, failed to decrease its Nr emission intensity with urbanization. However, Tianjin increased its Nr emission intensity all the way at the same time. These changes showed that the impacts of urbanization on the sub-regions within agglomeration were

different. Overall, the temporal variation of Nr emission intensity (annual 4.9 t N·km⁻²) of agglomeration was similar to that of Hebei, the results of Pearson correlation analysis showed that the Nr emission intensity of Hebei significantly affected

emission intensity of agglomeration ($r=0.989, P=0.000$), which meant that the reduction of Hebei's Nr emission intensity was the key to the overall reduction of Nr emissions to environment within the agglomeration.

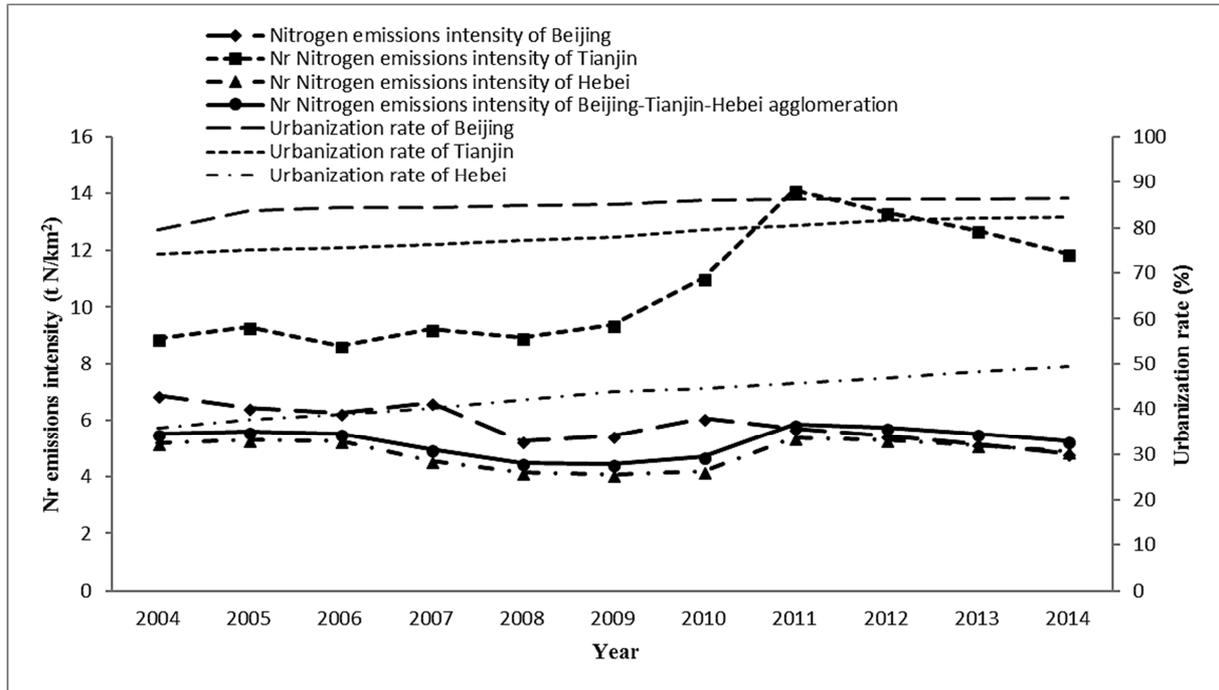


Figure 3 Nitrogen emission intensities of Beijing-Tianjin-Hebei agglomeration and urbanization rates during 2004-2014.

3.2. The Evaluation of Nr Removal Efficiency by Beijing-Tianjin-Hebei Agglomeration

Using the DEA model detailed above, the results showed that Beijing city achieved most efficient years for Nr removal without any inefficient years during sturdy period, indicating that the higher Nr removal efficiency by municipal government in Beijing contributed to the minimizing the Nr emissions in the progress of urbanization. However, Tianjin city achieved most inefficient years for Nr removal, mainly during 2009—2013, this illustrated why the Nr emissions by Tianjin began to over Beijing's emissions since 2008, with high level of Nr emission intensity at the same time. In term of

water, land and energy consumption, the amount of resource consumption for urbanization by these two cities were similar. However, Beijing's environment investment for pollutant control was 2 times more than Tianjin's investment, contributing to Beijing efficiently reducing more Nr emissions than those reduced by Tianjin. As the biggest Nr emitter in the agglomeration, Hebei province also had inefficient years. In view of the Nr removal efficiency by municipal governments in Beijing-Tianjin-Hebei agglomeration based on the DEA analysis, Beijing achieved most efficient in the Nr emissions reduction, followed by Hebei and Tianjin in order.

Table 3. Removal efficiency of Beijing-Tianjin-Hebei agglomeration from DEA analysis.

Year	Efficiency from VRS			Output slack			Targeted emissions (Gg N)		
	Beijing	Tianjin	Hebei	Beijing	Tianjin	Hebei	Beijing	Tianjin	Hebei
2004	1	1	1	0	0	0	-	-	-
2005	1	1	0.946	0	0	0.26	-	-	984.26
2006	0.994	1	0.949	0	0	0.14	-	-	984.26
2007	0.957	0.990	0.988	0	3.836	0	-	100.60	-
2008	1	1	1	0	0	0	-	-	-
2009	0.977	0.897	1	0	2.190	0	-	103.86	-
2010	0.962	0.887	1	0	15.364	0	-	104.55	-
2011	0.929	0.887	0.881	0	27.350	0.39	-	110.94	984.26
2012	0.940	0.826	1	0	28.577	0	-	105.28	-
2013	0.963	0.910	0.945	0	19.292	0	-	112.38	-
2014	1	1	0.935	0	0	0	-	-	-

This study does have some limitations in the analysis mentioned above. Owing to the lack of local annual statistics,

some parameters used in Nr emissions estimation were retrieved from the recent peer studies and some coefficients

for the estimation from 2004 to 2014 were merely based on the available data for 1 year, which might introduce potential uncertainties. Moreover, this study assumed that the environmental technology for Nr removal in Beijing city, Tianjin city and Hebei province did not vary significantly during research period while applying the DEA model, which would lead to bias evaluation results of annual removal efficiency. In reality, it is likely that the technologies for Nr reduction in some of regions improved gradually over the study period, such as the improvement of wastewater treatment technologies in some wastewater treatment facilities and the equipment of industrial waste gas purification in some factories. For future research, more in-depth research was needed to improve the accuracy of results and minimize bias introduction during evaluation.

3.3. The Nitrogen-Reduction Countermeasures Basing on ‘N Offset’ Mechanism

The concept of ‘N offset’ was primarily originated from the concept of ‘nitrogen-neutrality’ carried out by Leip [38] in 2014, which proposed to buy nitrogen quotas via financial subsidies to compensate for the excessive Nr emissions. The 6th International Nitrogen Conference, which was held in Uganda in 2013, participants supported the local afforestation via financial donation to minimize soil erosion and improved the soil fertility in the specific farmland, aiming at reducing the Nr loss though fertilizer application in the future, neutralizing the direct and indirect Nr emissions caused by the participants’ settlement in this conference [38]. Similar to ‘nitrogen-neutrality’, the ‘N offset’ mechanism for pollutant control during urbanization could be interpreted as that N offset could be purchased by government to neutralize the excess Nr emissions in a previous inefficient year with output slack by supporting low N-producing projects, thus encompassing a reduction of Nr emissions elsewhere in the local region during a specific period. This ‘N offset’ mechanism would stimulate the local government to achieve more efficient years since the costs of subsequent N offset

were generally higher for the additional compensation project establishment. According to the results of Nr removal efficiency evaluation mentioned above, Tianjin city and Hebei province needed to purchase subsequent N offset for additional compensation project establishment to neutralize the excess Nr emissions (the amount of Nr emissions that needed to be neutralized was calculated as the difference between current annual emission and minimized emission stimulated by the DEA model to achieve an efficient year) in previous inefficient years after 2014. Some studies found that the food nitrogen footprints (the upstream and downstream Nr loss during food production and consumption) of Beijing presented increased trend from 2004—2012, however, in this study the urban Nr emissions did not significantly increase. Consider that the food consumed by Beijing city were relying on the food import from Hebei province, it was possible that the most of Beijing’s food nitrogen footprints were outsourced to Hebei province, therefore, Beijing theoretically should share Hebei’s subsequent N offset to promote the coordinated development of agglomeration in term of Nr mitigation. The quotas allocation for Beijing in the neutrality of future Nr emissions could base on the percentage of agricultural Nr emissions to total emissions by Hebei in inefficient years. The table 4 showed that Beijing-Tianjin-Hebei agglomeration need to additionally reduce Nr emission (229.94 Gg N), the amount of which was approximately equal to the total annual emissions by Beijing and Tianjin, to neutralize the excess emissions by agglomeration in previous inefficient years. This goal was hard to be achieved in short term by Tianjin and Hebei with lower Nr removal efficiency. Therefore, in the mode of future N offset mechanism application, the collaborative N offset mechanism (Beijing with higher Nr removal efficiency shared the quotas of Hebei’s reduction of Nr emissions in future) was supposed to be more efficient than urban N offset mechanism (Tianjin and Hebei separately achieved objective Nr emission in future by themselves) in term of the completion of overall Nr neutrality as soon as possible.

Table 4. The emissions of Beijing-Tianjin-Hebei agglomeration for N-offset based on different N-offset mechanisms.

N-offset mechanism	Regions	Emission for N-offset (Gg N)
Urban N-offset mechanism	Beijing	0
	Tianjin	151.22
	Hebei	78.72
Collaborative N-offset mechanism	Beijing	36.06
	Tianjin	151.22
	Hebei	42.66
Regional N-offset mechanism	Beijing- Tianjin- Hebei agglomeration	229.94

3.4. The Pecuniary Compensation for ‘N Offset’ Mechanism

As being mentioned, the application of collaborative N offset mechanism would promote the efficiency and enforceability for the future N reduction to achieve Nr neutrality in the Beijing-Tianjin-Hebei agglomeration through Beijing city sharing Hebei’s quotas. Compared with this approach, the pecuniary compensation would be an alternative approach for the implement of ‘N offset’ strategy, which

would stimulate the regional government (Beijing and Hebei) to adopt the mechanism since the fiscal subsidies from Beijing city could be the financial investment for upgrade of clean production technologies to improve Nr removal efficiency in Hebei. Moreover, it is more practical for the current government of Beijing city to fulfill the duty to share the quotas of Hebei’s reduction of Nr emissions though immediate pecuniary compensation in case of leaving this political task to next government. To link the financial cost and various Nr

emissions, this study adopted the cost-benefit analysis to reveal the damage costs [42] (the financial cost referred to economic costs of various Nr species to the ecosystem and human health) of regional Nr emissions to quantify the amounts of pecuniary compensation from Beijing to Hebei (Table 5). The table showed that the ratios of damage costs caused by Nr emissions to regional GDP in Hebei province (1.8%) were much higher than Beijing (0.3%) and Tianjin (0.5%) cities. Therefore, during the study period, Hebei province was accelerating its urbanization level with higher environmental and health costs despite of its overall lower urbanization level, while Beijing city with lower costs continued maintaining its urbanization process along with its

overall higher urbanization level. The amounts of pecuniary compensation from Beijing to Hebei should be consistent with the quotas of subsequent N offset (36.06 Gg N) shared by Beijing, which could be calculated basing on the average percentages of various Nr emissions (NH₃ volatilization 72%, NO_x emission 0%, N₂O emission 1%, leaching and runoff 27%) to the total agricultural Nr emissions by Hebei province. Therefore, the value of pecuniary compensation (1090 million yuan) should be paid by Beijing city to fulfill its share of future Nr neutrality by Hebei province. In this case, the bilateral pecuniary compensation provides a more flexible approach for the implementation of collaborative N offset mechanism.

Table 5. Various reactive nitrogen emissions of Beijing- Tianjin- Hebei agglomeration with their damage costs.

Item	The coefficients for damage costs (¥/kg N)	Beijing		Tianjin		Hebei		The neutralized emissions shared by Beijing (Gg N)	Average damage cost (×10 ⁸ yuan)
		Average annual emissions (Gg N)	Average damage cost (×10 ⁸ yuan)	Average annual emissions (Gg N)	Average damage cost (×10 ⁸ yuan)	Average annual emissions (Gg N)	Average damage cost (×10 ⁸ yuan)		
NH ₃ volatilization	37.5	18.5	7.0	23.2	8.7	376.9	141.3	26.1	9.8
NO _x emission	29.6	59.9	17.7	72.5	21.5	404.1	119.6	/	/
N ₂ O emission	83.7	0.2	0.1	0.3	0.2	3.3	2.7	0.2	0.2
N leaching and runoff	9.3	19.4	1.8	24.7	2.3	138.6	12.9	9.76	0.9
Ratio between total damage cost and GDP (%)	/	/	0.3	/	0.5	/	1.8		

3.5. Policy Implication

Under the background of national promotion of collaborative development, the Beijing-Tianjin-Hebei agglomeration should together confront the challenges from environmental problems during collaborative urbanization. Some pollutant control policies issued by regional governments, including ‘Environment pollution control target and countermeasures’ in Beijing city [39], ‘Blue Sky Project’ in Tianjin city and ‘Pollutant Emissions Regulations’[40] in Hebei province, had positive impacts on the reduction of regional pollutant emissions such as chemical oxygen demand, sulfur dioxide, smoke and dust. However, their emissions intensities still were stronger than those in other agglomerations. Based on the results of this study, the Nr emissions by Beijing-Tianjin-Hebei agglomeration did not present significant decrease with urbanization, the current mode of collaborative development would not promote the sustainable development of whole agglomeration in terms of Nr mitigation. To address this challenging, the upgrade of pollutant control technologies and improvement of environmental regulations are needed, the former targeted to the mitigation of gaseous Nr pollution, the latter addressed the reduction of aquatic Nr loss [43]. In view of the different urbanization level and economic development model, Beijing, Tianjin and Hebei should optimize their configuration of industrial structures to realize the sustainable development of mutual complementary, to avoid promoting temporary sustainable development with low pollution in one city at the cost of the transferences of pollution industries to other city and province within the agglomeration. In this case, the rates of food self-sufficiency in Beijing city, as well as fiscal

subsidies for agricultural production in original places, should be appropriately increased to ease the burden of food provision by Hebei province. Meanwhile, the environmental investments should be increased to upgrade the pollutant control technologies to modify the important point source of Nr emissions in the city and industry scales, including the Tangshan city within Hebei province where most steel production factories located, and the biggest power station in Tianjin city. On the basis of mentioned countermeasures, the collaborative N offset mechanism was employed to achieve the goal of mutual Nr reduction in the process of continuing urbanization promoted by the China State Council [44], which contributed to the sustainable and collaborative development of the whole agglomeration.

4. Conclusion

This study served as a baseline work for the future research on evaluation of Nr emissions reduction in urbanized areas towards collaborative development. The main conclusions were summarized as follows:

(1) During 2004—2014, in the process of rapid urbanization, the total reactive nitrogen emissions by Beijing-Tianjin-Hebei agglomeration presented slightly decreased with fluctuation. Hebei province was the main contributor to nitrogen emission, occupying 79-84% and 74-79% of nitrogen loss to atmosphere and hydrosphere. The main sources of regional emissions were agricultural activities primarily, and then turned to industrial activities and residential livelihood. The differences existed in the impacts of urbanization on reactive nitrogen emission intensity of each region. The annual emission intensity of this agglomeration

was 5.8 t N/km², which was driving by that of Hebei province.

(2) Based on the results of the evaluation of Nr removal efficiency by applying DEA model, Beijing achieved most efficient in the Nr emissions reduction, followed by Hebei and Tianjin in order from 2004 to 2014. Through the implementation of collaborated 'N offset' mechanism, the governments of these regions can purchase subsequent N offset to neutralize the excess Nr emissions in previous inefficient years, and the pecuniary compensation (1090 million yuan) should be paid by Beijing to help Hebei to achieve its Nr neutrality. Meanwhile, the environmental investment for upgrade of pollutant control technologies and improvement of environmental regulations for further pollutant control are needed to improve Nr removal efficiency. The reduction of Nr emission intensity of Hebei province and improvement of Nr removal efficiency of Tianjin city were supposed to be the keys for overall low-nitrogen urbanization within agglomeration. The method applied in this case study in Beijing-Tianjin-Hebei agglomeration could provide theoretical references for governments in other regions in China to minimize the Nr emissions with rapid urbanization.

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