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Economic environmental imbalance in China — Inter-city air pollutant emission linkage in Beijing–Tianjin–Hebei (BTH) urban agglomeration

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ABSTRACT

Production fragmentation makes the air pollution policy no longer at the local scale but requires accounting more about embodied emissions cross-region through supply chains. Here, we map the consumption-driven NO_x networks of Beijing-Tianjin-Hebei urban agglomeration (BTH) in China using the city-level multi-regional input-output model. The results show that the construction, service, and equipment manufacturing sectors in Beijing and Tianjin indirectly drive more than half of BTH NO_x emissions (54%). Moreover, 75% of NO_x flows in the supply chains are traded from cities with low efficiency (high intensity) to cities with high efficiency (low intensity), which reflects the economic environmental imbalance in BTH. Especially, for the metals smelting and pressing sector and nonmetal mineral products sector, there is a wider gap in emission intensity between production-oriented cities (1.03–4.43 Mt/million yuan) and consumer-oriented cities (0.08–0.45 Mt/million yuan), which leads to additional emissions of air pollutants to increase. At the same time, for the provinces in the south and north China, the role of BTH in the supply chain is different, which leads to an economic environmental imbalance between the north and the south. Synchronous outsourcing of production and technology is the key to solving the economic environmental imbalance. The consumption-oriented high-income cities are suggested to increase the financial and technical support to improve the efficiency of pollution control in production-oriented cities.

1. Introduction

With the rapidly increasing output of industrial products and services in China, the total amount of air pollutant emissions are still increasing in China, which has caused serious air pollution issues with high concentrations of $PM_{2.5}$ and O_3 (Huo et al., 2014; Miao et al., 2020). The control of NO_x is one of the key steps in reducing $PM_{2.5}$ and O_3 levels (Sillman et al., 1990). The Beijing-Tianjin-Hebei urban agglomeration (the abbreviation of this region is BTH) is one of the regions in China with the most severe air pollution. The division of labor among cities in BTH has taken shape. High-tech service industries and cultural industries are mainly concentrated in Beijing and Tianjin. Hebei cities' manufacturing industry is developing rapidly and its secondary industry has obvious advantages (National Bureau of Statistics of China, 2021). For example, Hebei is the largest steel production province in China, and the iron and steel enterprises are mostly located in Tangshan and Handan. Hebei's crude steel output reached 240 million tons in 2019, accounting for nearly a quarter of China. In recent years, a large number of measures have been put in place to deal with air pollution issues in BTH. In general, it is required to ban substandard enterprises and comprehensively promote emission permit management (Ministry of Ecology and Environment of PRC, 2019a). Among them, steel enterprises in BTH are required to complete the transformation of ultra-low emissions by the end of 2025 (Ministry of Ecology and Environment of PRC, 2019b). Although China has invested 5.9 billion yuan in air pollution control in the Beijing-Tianjin-Hebei region and surrounding areas, the proportion of days that did not satisfy the national standard of air quality was as high as 46.9% in BTH (Ministry of Ecology and Environment of PRC, 2020). Although interannual meteorological variations could significantly alter air pollutant concentrations (Wang et al., 2019), the improvement in air quality was dominated by abatements in anthropogenic emissions rather than interannual variation in meteorological conditions (Zhang et al., 2019). There should be deeper socio-economic reasons. The socio-economic factors, such as production and consumption behavior, are the main factors leading to anthropogenic emissions, but there is still a lack of research in this field. Therefore, it is an

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important breakthrough to find solutions along the economic supply chain connecting consumption and production.

The development of high value-added manufacturing and service-based economy only has moderate environmental gains, and the supply chain can still be emission-intensive (Guan et al., 2014). Thus, it is not feasible to reduce direct emissions only from the perspective of pollution-intensive upstream industries, whereas the reduction of emissions along the whole supply chains to the downstream industries and service is the key to a low emission economy. In addition, the latest law of atmospheric pollution emphasizes collaborative efforts across administrative boundaries for emissions control and pollution prevention (Ministry of Ecology and Environment of PRC, 2018). Therefore, it is important to study how pollutants are transferred through the supply chains. Embodied emission is an index to describe inter-regional and sectoral linkages of air pollution through trade or supply chains (Wang et al., 2017). The input-output technique has been widely employed to study the embodied emission (Huo et al., 2014; Lenzen, 1998; Wang et al., 2017; Yang et al., 2018). Wang et al. (2017) analyzed the transfer patterns of embodied air pollutant emissions (SO_2, Soot, Dust and NO_x) flows in BTH urban agglomeration and found that the transfer pattern of air pollutant emissions is from the nonmetal products sector of Hebei province to the construction sector of Beijing in 2010. Some researchers established a multi-regional nexus network, based on ecological network analysis in BTH urban agglomeration and found that Beijing and Tianjin are dependent on Hebei for water and energy resources, while Hebei is more self-sufficient (Wang and Chen, 2016). Yang et al. investigated the transfers of embodied $PM_{2.5}$ emissions to and from the North China region and found that Beijing and Tianjin mainly transferred embodied pollution to Hebei and Shanxi provinces, whilst Jiangsu, Shanghai, and Zhejiang provinces tended to import embodied air pollutants from Shandong and Henan provinces. Zhao et al. contrasted economic gains against atmospheric pollutant emissions in 2010 and the CO_2 emissions associated with international and interprovincial exports from Beijing–Tianjin–Hebei (BTH). They found that most of the emissions of BTH embodied in exports went to neighboring provinces and developed coastal areas in eastern China.

The previous researches have made a good calculation of the embodied pollutants in the Beijing-Tianjin-Hebei urban agglomeration from province-level perspectives. Some latest studies focus on the balance of the economic environment in the BTH region from the city level, but few studies focus on NO_x (Bai et al., 2021; Guo et al., 2021; Liu et al., 2021). Thus, there is a gap within the existing body of knowledge, i.e. the previous researches are based on the province level and ignore the heterogeneity of the 11 cities in Hebei province, such as industrial division and distribution, which are difficult to be applied to the urban pollution control practice. The results based on the city-level resolution may differ from those based on provincial resolution. Exploring the embodied transfer of air pollution at the city level can provide a scientific basis for the fine air pollution management policy of "one city and one policy", and also help to find the key urban for collaborative emission reduction.

To bridge the gap, this paper maps the consumption-driven NO_x networks related to BTH using the city-level multi-regional input-output model and analyzes the economic environmental imbalance of key sectors. The reason for choosing NO_x as the research pollutant is the NO_x emissions in BTH are large and much higher than SO_2 and particulate matter (National Bureau of Statistics of China, 2021), and as one of the important precursors of $PM_{2.5}$ and O_3, it is an important cause of serious secondary pollution today (He et al., 2019; Sillman et al., 1990). Although reductions in NO_x may increase ozone concentrations in the short-term (Li et al., 2021), in the long run, reducing the emission of NO_x is conducive to the improvement of atmospheric environmental quality. In addition, NO_x has been included in major indicators of environmental protection by the Chinese government since 2011(The Communist Party of China, 2011). Therefore, it is crucial to understand NO_x emissions from the perspective of economic activities, as theoretical support for regional atmospheric management. This study aims at better understanding the inter-city and sectoral linkages of NO_x emission and identifying key cities and their key sectors that contribute to embodied emissions flows related to BTH. The results of this study could facilitate optimization of emission reduction targets for different cities, to balance pollution reduction and economic development.

2. Data sources and methodology

In this study, a flow chart of the construction and quantification of the methodology is shown in Fig. 1. Below we will describe each step in detail.

2.1. MRIO table and emissions inventory data

The study area was the Beijing–Tianjin–Hebei urban agglomeration (Fig. 2). including Beijing, Tianjin, and 11 cities in Hebei province. City abbreviations and province abbreviations are in Table S1. The multi-region input-output table contains 26 sectors (see Table S2).

To reveal the transfer patterns of embodied pollutants emissions flows of the city level, the 2017 city-level MRIO table, which describes intermediate trade flow among 13 cities in BTH and 28 provinces. To match the city-level MRIO table, emissions data were compiled, which contains NO_x emissions from 26 sectors of 13 cities in BTH and the other 28 provinces in China. The NO_x emissions data are derived from the official environmental statistics emission database, which were aggregated from 397,720 enterprises (Table S5). The NO_x emission data for non-industrial sectors are estimated based on the national average emission intensity and primary energy consumption (not including electricity) of each sector.

2.2. Update of 2017 city-level MRIO – ANAIS model

Generally, in a multi-region input-output (MRIO) model, national input-output tables represent financial transactions between economic sectors within a country, and trade flow tables. (Wiedmann et al., 2011). In this paper, city-level MRIO subdivides the region into cities. We update the 2017 city-level MRIO based on the ANAIS model (Tarancón and Río, 2005) according to the 2012 Beijing-Tianjin-Hebei MRIO table (China Emission Accounts and Datasets, 2021). The table contains 26 economic sectors and 40 regions (Fig. 3), including 13 cities in BTH and 28 other provinces or municipalities (excluding Taiwan, Hong Kong, and Macao due to data availability). In Fig. 3, $\mathbf{X}$ denotes the intermediate deliveries matrix, $\mathbf{Y}$ denotes the final demand matrix, $\mathbf{Z}$ denotes the primary inputs matrix, $\mathbf{W}$ denotes the gross input matrix, and $\mathbf{W}^{\mathbf{T}}$ denotes the gross output matrix.

Due to the high cost and long time lag of using survey methods to compile input-output tables, it is particularly important to use mathematical methods to estimate and update input-output tables. The methods of updating input-output table include RAS method and mathematical programming method (Xia and Zhang, 2019). However, the use of the RAS method requires various departmental output, added value, final demand, and other information, which may not be available. Mathematical programming has developed many different models. Lars Bohlin and Lars M. Widell constructed four types of specific models (ITA, CTA, MIX, MIC) based on published manufacturing table and usage table data of Sweden (Xia and Zhang, 2019), and Miguel Angel Tarancon and Padlo del Rio (2005) proposed the ANAIS model. The model constructed by Lars Bohlin and Lars M. Widell can solve the flaws in the product process assumptions, but the error is larger in the business sectors. The ANAIS model has great advantages. If the row sum and column sum of the adjustment matrix cannot be known exactly, the ANAIS calculation result is better than the RAS method (Tarancón and Río, 2005).

Therefore, this study uses the ANAIS model to update the 2017 city-level MRIO with input-output related data in 2017. In this study, 2017

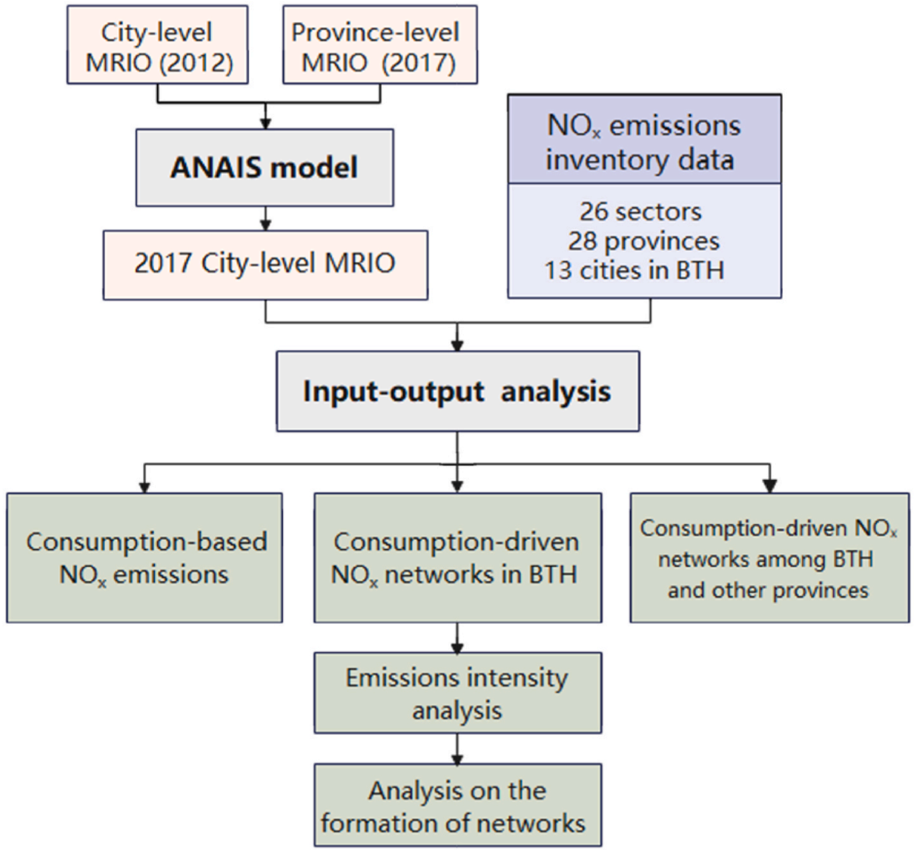


Fig. 1. The flow chart of the study.

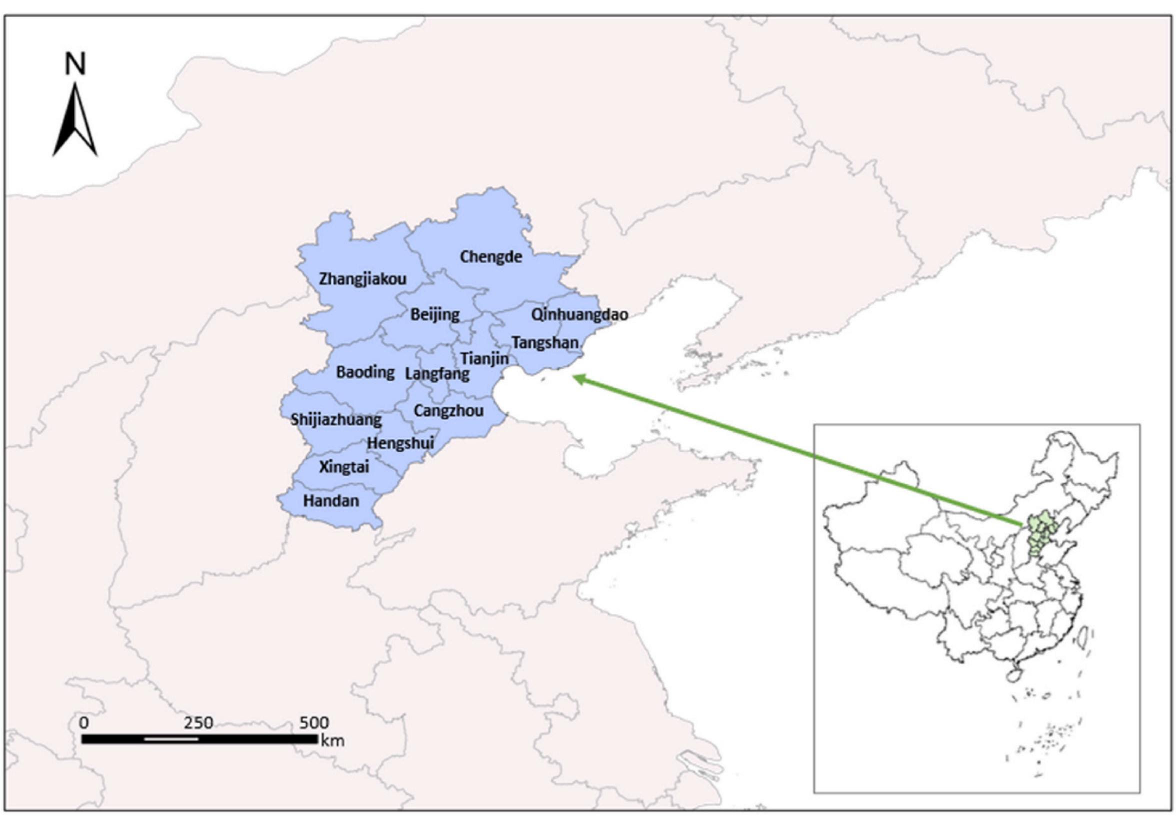


Fig. 2. Location of the Beijing–Tianjin–Hebei urban agglomeration (BTH).

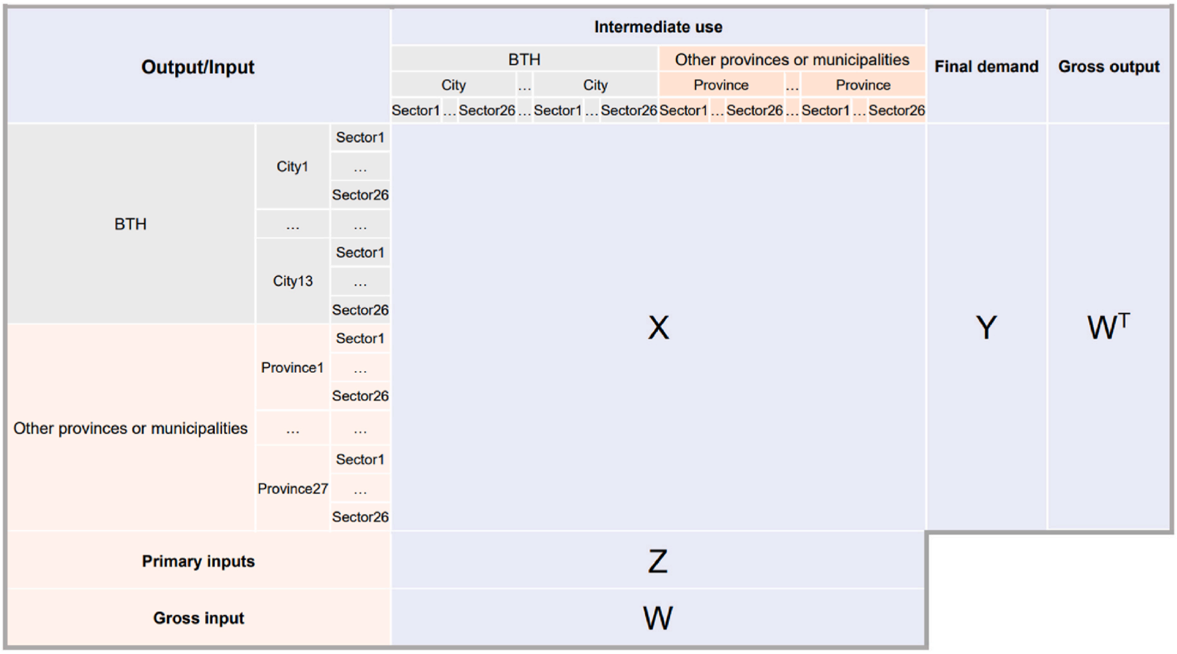


Fig. 3. City-level MRIO

city-level MRIO can be derived based on the methodology designed as follow. The following data are available with certainty: 2012 city-level MRIO classified into 26 sectors and 2017 province-level MRIO classified into 26 sectors. The main problem found is the lack of sectoral input-output data of Heibei cities.

ANAIS model is built on the hypothesis of a stable structural evolution (Tarancón and Río, 2005). The following mathematical programming model is constructed:

$$min\sum_{ij}\left\{\left|\frac{x_{ij}^{0}-x_{ij}^{*}}{x_{ij}^{0}}\right|\right\}+\sum_{ik}\left\{\left|\frac{y_{j}^{0}-y_{j}^{*}}{y_{j}^{0}}\right|\right\}+\sum_{dj}\left\{\left|\frac{z_{i}^{0}-z_{i}^{*}}{z_{i}^{0}}\right|\right\} \tag{1}$$

where x_{ij}^{0} denotes the elements of the reference matrix of intermediate deliveries $\mathbf{X}^{0}$, x_{ij}^{*} denotes the elements of the adjusted matrix of intermediate deliveries, y_{j}^{*} (y_{j}^{0}) and z_{i}^{*} (z_{i}^{0}) respectively denote the elements of the adjusted (reference) final demand matrix $\mathbf{Y}^{*}$ ($\mathbf{Y}^{0}$) and the adjusted (reference) primary inputs matrix $\mathbf{Z}^{*}$ ($\mathbf{Z}^{0}$), the adjusted (reference) MRIO denote 2017 city-level MRIO (2017 city-level MRIO),and i, j respectively denote the sequence number of the row and column.

The objective function, which is not linear, needs to be modified. In addition, the relative discrepancies being smaller than a certain level *rmax* need considered. This leads to the following hierarchical multi-objective linear programming problem (Tarancón and Río, 2005).

$$\begin{cases}\min rmax \\ \min\left(\sum_{i,j}r_{ij}^{x}x_{ij}^{0}+\sum_{i}r_{i}^{y}y_{i}^{0}+\sum_{j}r_{j}^{z}z_{j}^{0}\right)\end{cases} \tag{2}$$

subject to follow equations (3)–(9):

$$r_{ij}^{x},\ r_{i}^{y},\ r_{j}^{z}\geq 0 \tag{3}$$

$$x_{ij}^{0}\left(1-r_{ij}^{x}\right)\leq x_{ij}^{*}\leq x_{ij}^{0}\left(1+r_{ij}^{x}\right)\quad \forall i,j \tag{4}$$

$$y_{i}^{0}(1-r_{i}^{y})\leq y_{i}^{*}\leq y_{i}^{0}(1+r_{i}^{y})\quad \forall i \tag{5}$$

$$z_{j}^{0}\left(1-r_{j}^{z}\right)\leq z_{j}^{*}\leq z_{j}^{0}\left(1+r_{j}^{z}\right)\qquad \forall j \tag{6}$$

$$r_{ij}^{x}x_{ij}^{0}\leq rmax\quad \forall i,j \tag{7}$$

$$r_{i}^{y}y_{i}^{0}\leq rmax\quad \forall i \tag{8}$$

$$r_{j}^{z}z_{j}^{0}\leq rmax\quad \forall j \tag{9}$$

Other restrictions include:

(1) Consistency equations:

$$\begin{cases}\sum_{j}y_{j}^{*}=\sum_{i}z_{i}^{*} \\ \sum_{j}x_{ij}^{*}+y_{i}^{*}=w_{i}^{*} \\ \sum_{i}x_{ij}^{*}+z_{j}^{*}=w_{j}^{*}\end{cases} \tag{10}$$

(2) Coherence equations are employed to avoid variations in the coefficients that are difficult to accept from the production perspective.

$$a_{ij}^{-}\leq\frac{x_{ij}^{*}}{w_{j}^{*}}\leq a_{ij}^{+} \tag{11}$$

That is, the range of technical coefficient a_{ij}^{*} is $[a_{ij}^{-},\ a_{ij}^{+}]$. The range of technical coefficient of a certain sector is estimated by the range of technical coefficient of this sector in Chinese provinces in 2017.

(3) Consistency of economic aggregates:

$$\begin{cases}y_{Hebei,2017}^{*}=y_{Hebei,2017}^{0} \\ z_{Hebei,2017}^{*}=z_{Hebei,2017}^{0} \\ w_{Hebei,2017}^{*}=w_{Hebei,2017}^{0}\end{cases} \tag{12}$$

That is, the sum of final demand (y_{j}^{*}), primary input (z_{i}^{*}), and gross input (w_{i}^{*}) of all cities in Hebei in our updated 2017 city-level MRIO are equal to that of Hebei in the 2017 province-level MRIO.

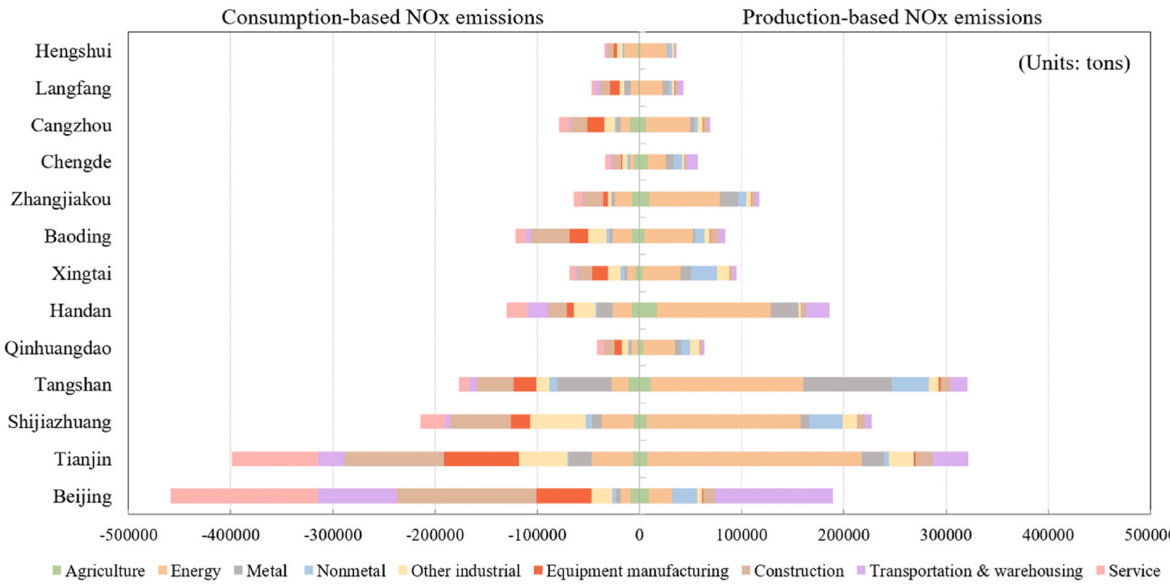


Fig. 4. Production- and consumption-based NO_x emissions in 13 cities in BTH (Units: tons). In order to express more concisely and intuitively, 26 sectors were merged into 9 sectors, namely agriculture, energy, metal, nonmetal, other industrial, equipment manufacturing, construction, transportation & warehousing, service (Table S3).

2.3. City-level MRIO analysis

In the early seventies, already Leontief, among others, extended the analysis to cover environmental aspects within the input-output (IO) analysis (Leontief, 1970). Nowadays, the Environmentally Extended Input-Output (EEIO) Analysis is widely used (Huo et al., 2014; Lenzen, 1998; Li et al., 2020; Wei et al., 2021). To include any environmental extension, we need to have an additional matrix or vector that provides the amount of pollutants, i.e., emitted by each activity sector per monetary unit of output. We get the final expression that we have used in this study:

$$\mathbf{C} = \mathbf{E}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{Y} \tag{13}$$

where C is consumption-based NO_x emissions, E is a vector whose elements are defined as the amount of direct NO_x emissions per unit total output, matrix $\mathbf{A}$ is the technical coefficient matrix, $\mathbf{A} = (a_{ij}^{rs})_{n\times n}$, $a_{ij}^{rs} = \frac{x_{ij}^{rs}}{z_j^s}$, $(\mathbf{I} - \mathbf{A})^{-1}$ is the Leontief inverse matrix, and Y is the final demand (Wang et al., 2017).

Equation (13) can be written as:

$$\begin{bmatrix} c_1^1 \\ \vdots \\ c_i^r \end{bmatrix} = diag\begin{bmatrix} e_1^1 \\ \vdots \\ e_i^r \end{bmatrix}\left(I - \begin{bmatrix} a_{11}^{11} & \cdots & a_{1j}^{1s} \\ \vdots & \ddots & \vdots \\ a_{i1}^{r1} & \cdots & a_{ij}^{rs} \end{bmatrix}\right)^{-1}\begin{bmatrix} y_1 \\ \vdots \\ y_r \end{bmatrix} \tag{14}$$

where c_i^r is consumption-based NO_x emissions of sector i in region r (unit: ton), e_i^r is the direct NO_x emissions per unit total output (unit: ton/yuan) and *diag* denotes vector diagonalization, a_{ij}^{rs} denotes the value of product or service from sector i in region r to produce unit output for sector j in region s, y_r denotes the final demand of region r (unit: yuan), and $i,\ j\ (r,\ s)$ denote regions (sectors).

The inter-regional and sectoral linkages can be represented by the flows of embodied NO_x emissions between sectors in different regions. Embodied NO_x emissions that transfer from sector i in city r to sector j in city s can be extracted from the following equation:

$$\begin{bmatrix} f_{11}^{11} & \cdots & f_{1j}^{1s} \\ \vdots & \ddots & \vdots \\ f_{i1}^{r1} & \cdots & f_{ij}^{rs} \end{bmatrix} = diag\begin{bmatrix} e_1^1 \\ \vdots \\ e_i^r \end{bmatrix}\left(I - \begin{bmatrix} a_{11}^{11} & \cdots & a_{1j}^{1s} \\ \vdots & \ddots & \vdots \\ a_{i1}^{r1} & \cdots & a_{ij}^{rs} \end{bmatrix}\right)^{-1}\begin{bmatrix} x_{11}^{11} & \cdots & x_{1j}^{1s} \\ \vdots & \ddots & \vdots \\ x_{i1}^{r1} & \cdots & x_{ij}^{rs} \end{bmatrix} \tag{15}$$

where f_{ij}^{rs} denotes embodied pollutants that transfer from sector i in city r to sector j in city s (unit: ton), and x_{ij}^{rs} denotes the intermediate products transferred from sector i in region r to sector j in region s (unit: yuan).

3. Results

3.1. Production-based versus consumption-based accounting of NO_x emissions

Production-based emissions refer to the direct emissions in a given region. Consumption-based emissions refer to emissions generated by local final demand, i.e. the amount of the embodied emissions that are involved in intermediate production flows along production supply chains as well as the consumers of these products (Huo et al., 2014). According to equation (14), the consumption-based NO_x emissions in BTH were calculated using the MRIO method (Fig. 4).

From a regional perspective, Beijing and Tianjin have the largest consumption-based emissions in BTH, accounting for about 45.9%. Production-based emissions in Hebei are 29% higher than its consumption-based emissions, indicating Hebei Province is a production-oriented province. However, when we analyzed the cities in Hebei province, the consumption-based emission of central cities closed to Beijing and Tianjin (e.g. Langfang, Cangzhou, and Baoding) in Hebei Province is greater than production-based emission. There are also some cities in Hebei province, where consumption and production emissions are almost the same, such as Shijiazhuang. Only Tangshan, Zhangjiakou, Chengde in the north and Xingtai and Handan in the South truly show the production role of Hebei Province. Therefore, the role of each city in regional air pollution can be more accurately identified by analyzing it from the city level. For environmental managers, accurate policies can be formulated according to the different roles of cities, and more effective city-level joint prevention and control policies can be proposed.

From an industrial perspective, energy, transportation & warehousing, metals, and nonmetal mineral sectors are the major sectors contributing to production-based NO_x releases in BTH (85%). The energy sector is the leading production-based emissions in all the cities of BTH except Beijing (31–74%), while Beijing's main production-based emissions come from transportation & warehousing (61%). Construction, service, and equipment manufacturing sectors, especially in Beijing and Tianjin, are the major sectors contributing to consumption-based NO_x emissions (54%). Therefore, analyzing the embodied NO_x transfer flow of the three consumption-based sectors (construction, service, and equipment manufacturing sectors) is the key to analyzing the driving factors and emission reduction potential of air pollutants emissions in BTH. Besides, the spatial expression will help to analyze the emission responsibility between cities, and then formulate more effective and fair emission reduction targets. Therefore, we have done the following more detailed linkage study.

3.2. *Inter-city consumption-driven NO_x networks within the BTH region*

Under the framework of the input-output model, the inter-city-sector linkage of the embodied NO_x emission in trade can be measured according to equation (15) based city-level MRIO table. The results show there are three key consumption-driven NO_x networks, namely (a) construction sector consumption-driven NO_x network, (b) service sector consumption-driven NO_x network, and (c) metal products and equipment manufacturing sectors consumption-driven NO_x network (see Fig. 5).

Fig. 5a shows the main transfers of embodied NO_x emissions related

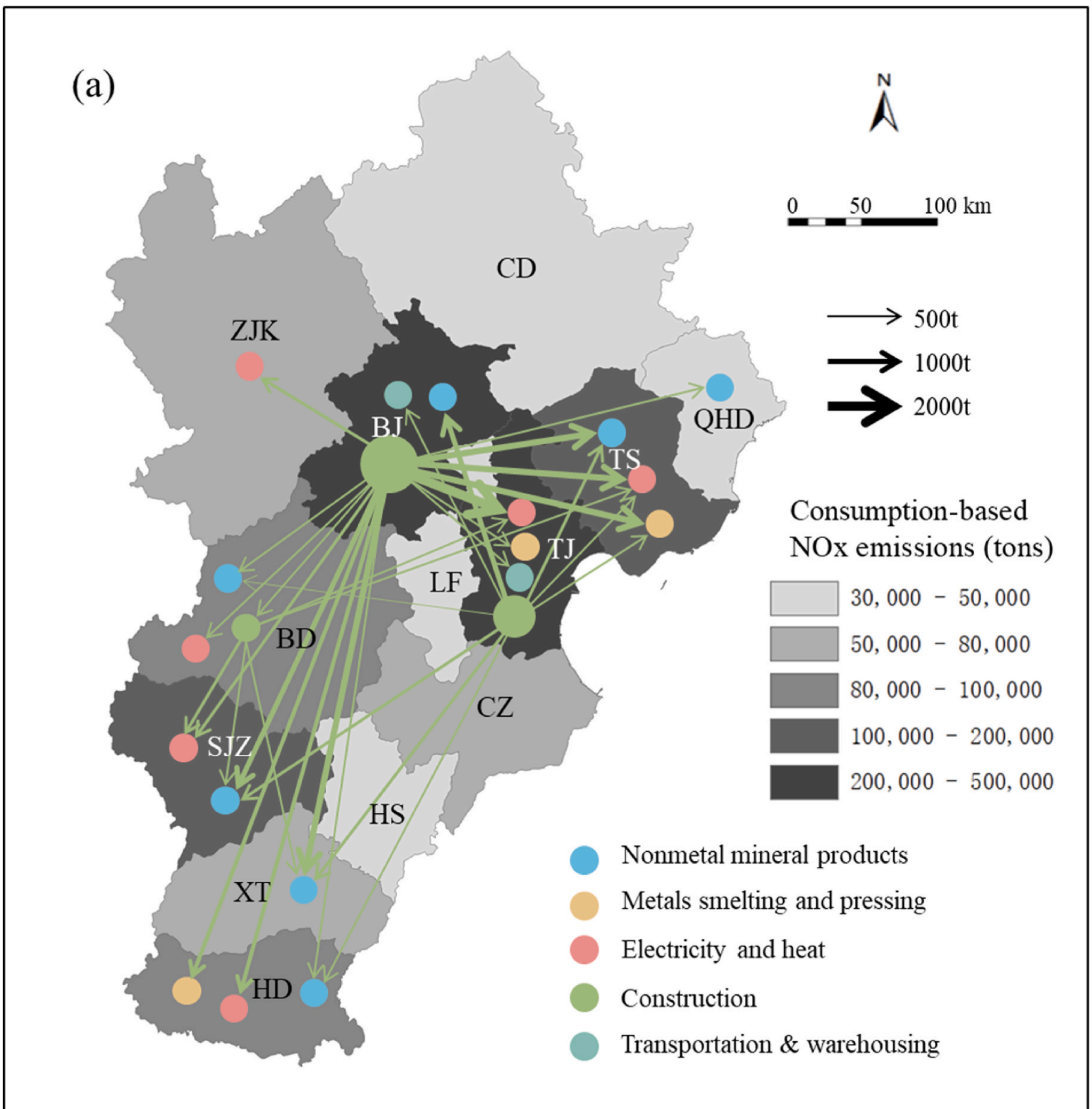


Fig. 5. Consumption-driven NO_x networks within BTH region (a) construction sector consumption-driven NO_x network, (b) service sector consumption-driven NO_x network, and (c) metal products and equipment manufacturing sectors consumption-driven NO_x network. The color of the point represents the sectors, and arrows indicate the transfer direction of NO_x emissions. Please refer to Table S1 for the abbreviations of city names. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

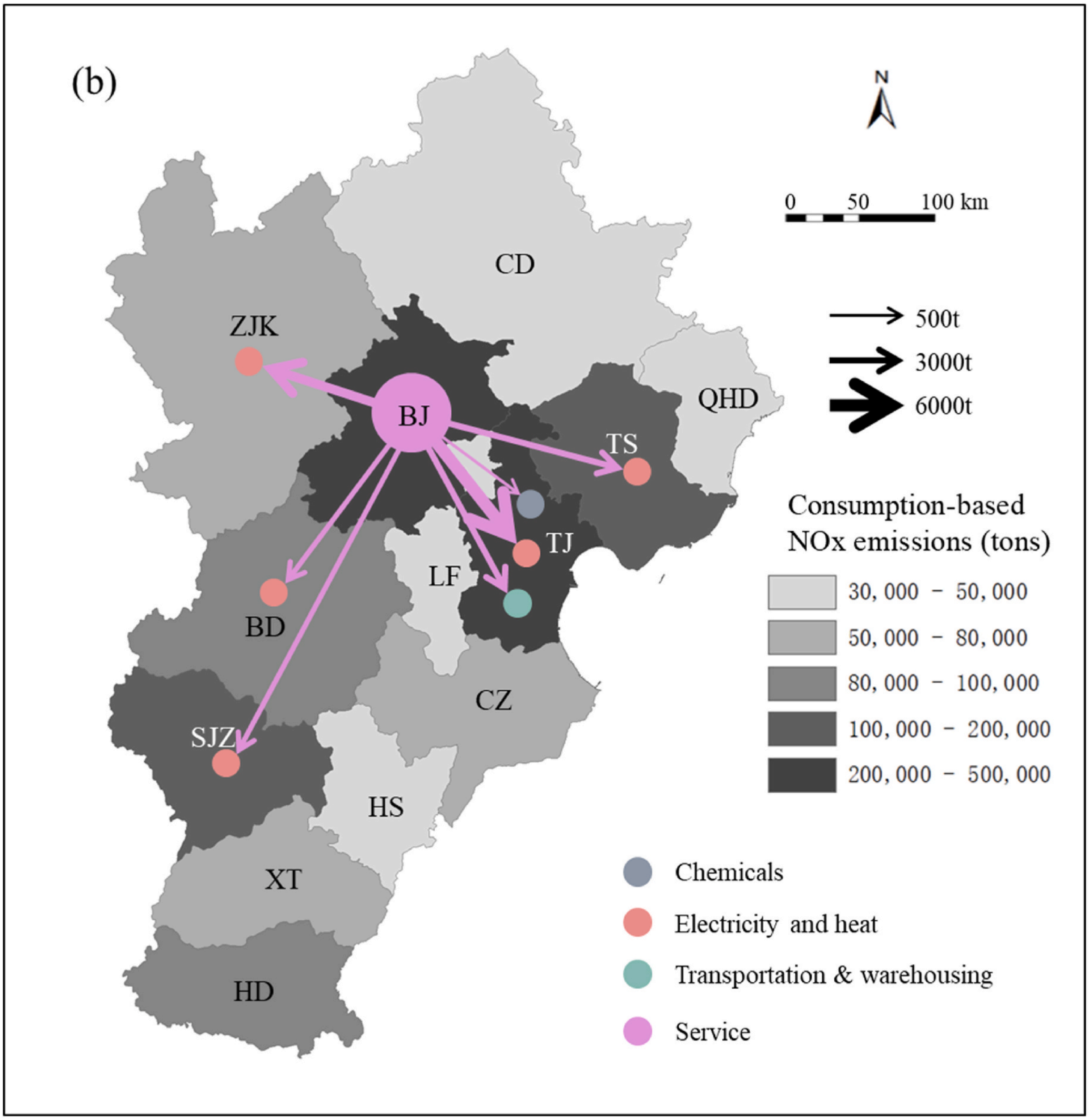


Fig. 5. (*continued*).

construction sector in BTH. The largest embodied NO_x exporter (final consumer) is the construction sector in Beijing (32,950t), followed by the construction sector in Tianjin (14,683t). The main upstream supply sectors of the construction sector in Beijing are nonmetal mineral products, metals smelting and pressing, and electricity & heat sectors located in the eastern (Tangshan, Qinhuangdao and Tianjin) and southwestern regions (Baoding Shijiazhuang, Xingtai, and Handan) of BTH. Meanwhile, embodied NO_x emissions flows are transferred from Beijing to these cities through the supply chains. The transfer pattern of embodied NO_x emissions of the construction sector in Tianjin is similar to the construction sector in Beijing but on a much smaller scale. This could be because the increasing number of young people in China choose to settle in big cities like Beijing and Tianjin which leads to expanding demand of the construction sector and drives the embodied emissions.

Fig. 5b shows the transfers of embodied NO_x emissions related to the service sector in BTH. The service sector in Beijing (30,048t) is also an important embodied NO_x exporter (final consumer), and the embodied NO_x emission caused by the service sector is transferred to other cities through goods and services. The biggest NO_x emission flow is from the service sector in Beijing to Tianjin, is mainly due to consuming the products from electricity & heat, transportation & warehousing, and chemicals sectors in Tianjin (23.42%, 8.17%, and 3.42%, respectively). The cities around Beijing (Tianjin, Zhangjiakou, Tangshan, etc.) provide electricity & heat for the service sector in Beijing, which may result in high NO_x concentrations surrounding Beijing.

Fig. 5c shows the transfers of embodied NO_x emissions related to metal smelting, products, and equipment manufacturing sectors in BTH. Beijing and Tianjin are important metal equipment manufacturing cities, these manufacturing sectors' output values account for 26.35% and 25.67% of BTH respectively (see Table S6). The equipment manufacturing sectors in Beijing and Tianjin are important embodied NO_x exporters. The metals smelting and pressing sector in Tangshan (8,295t) is the largest embodied NO_x importer (the main supplier), followed by metals smelting and pressing sectors in Handan (3986t) and Chengde (2,031t). The metal products, common & special equipment, transport equipment, electrical equipment sectors in Beijing consume the metal materials produced by Tangshan, Handan, and Chengde. For

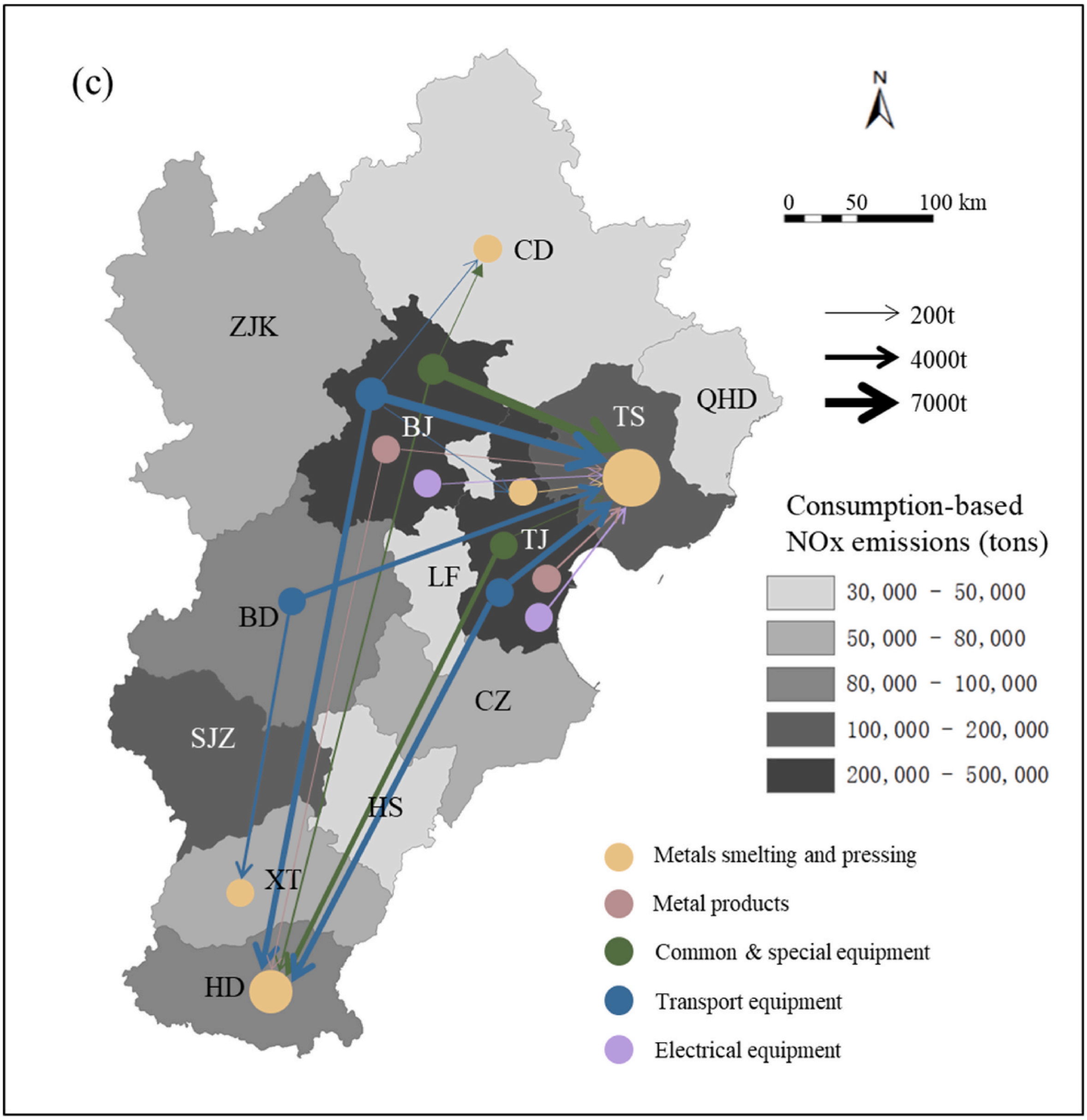


Fig. 5. (*continued*).

instance, the percentage of embodied NO_x transfers from these sectors to Tangshan is 6.29%, 14.76%, 14.80%, and 5.87% respectively.

3.3. Consumption-driven NO_x networks between BTH cities and other provinces

The above-mentioned sector linkages not only occur within the BTH cities, but also between the BTH region and other provinces. According to Fig. 6, most of the northern provinces of China around the BTH area (Inner Mongolia, Shanxi, Henan, and Liaoning Provinces) are the main embodied NO_x emissions importers (main suppliers), while the eastern coastal area to the south of BTH (Shandong, Jiangsu and Zhejiang Provinces) are the main embodied NO_x emissions exporters (final consumers). The cities (Beijing, Tianjin, and Tangshan) near the Bohai Sea in the BTH area are the key cities of consumption-driven NOx networks between BTH cities and other provinces.

3.3.1. The main embodied NO_x emissions importers (main suppliers)

The amount of embodied NO_x transfer from Beijing to Inner Mongolia is the most significant (27,530t), which is mainly due to the construction and Service in Beijing bought the products from metals smelting and pressing, metal products, coal mining and processing, transportation & warehousing sectors in Inner Mongolia. Construction in Tianjin also has a large amount of embodied NOx emissions (6,042t) transferred to Inner Mongolia, mainly because construction in Tianjin imports similar industrial raw materials from Inner Mongolia Province. The construction in Beijing and Tianjin has similar sector linkages with Henan and Liaoning provinces. Shanxi province in the west of BTH is different from other neighboring provinces. Shanxi's coal and power sectors are closely related to the construction sector in Beijing and Shijiazhuang.

3.3.2. The main embodied NO_x emissions exporters (final consumers)

The equipment manufacturing (common & special equipment, transport equipment, and electrical equipment sectors) in the Jiangsu and Shandong provinces mainly imports metal materials from Tangshan. The construction sector in Jiangsu and Zhejiang provinces mainly import metal and electricity from Tangshan, Tianjin, and Zhangjiakou.

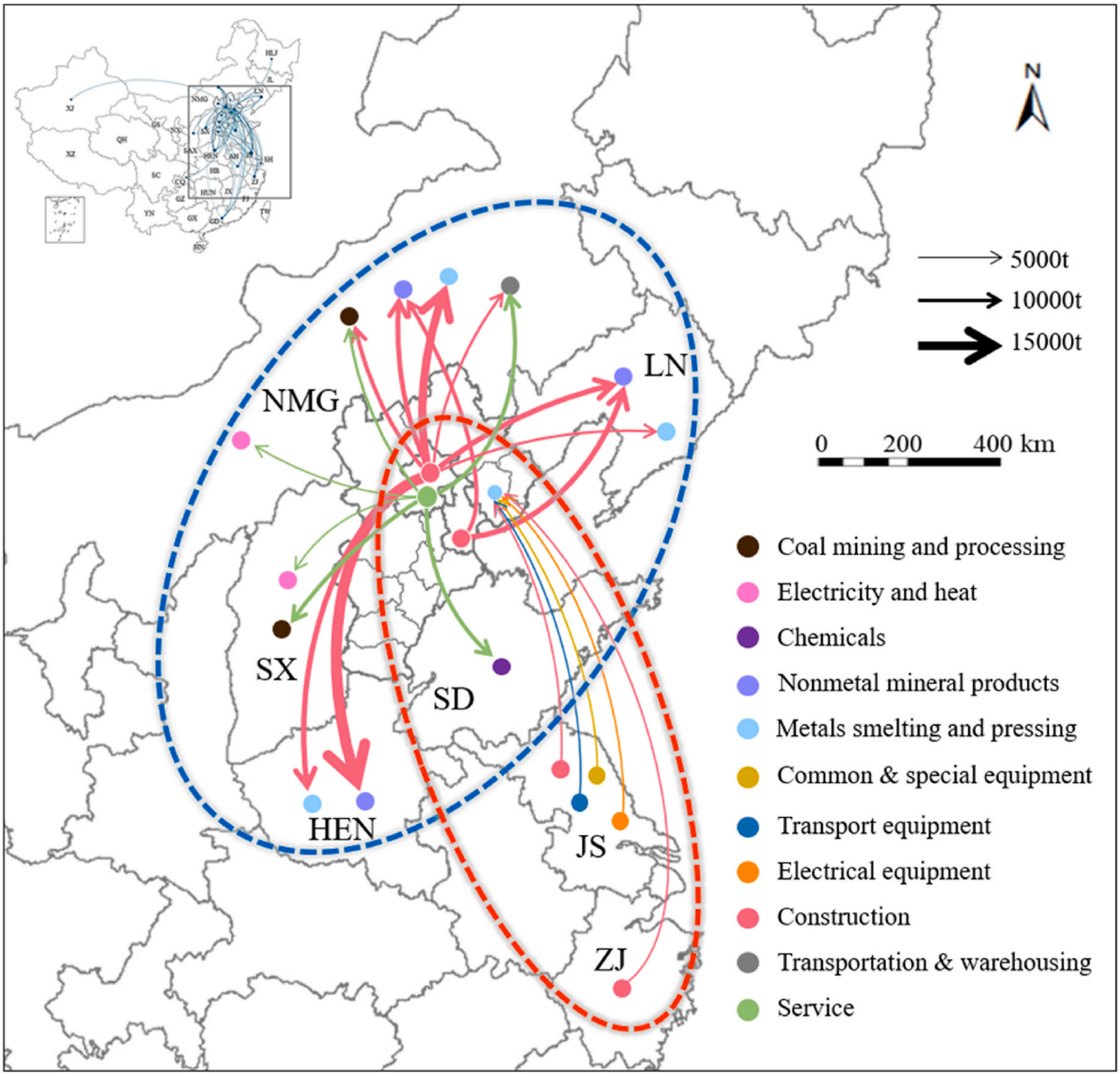


Fig. 6. Consumption-driven NO_x networks between BTH cities and other provinces.

Thus, the embodied NO_x emissions from these eastern coastal provinces of China transfer to those eastern and northern cities of BTH.

The blue circle is the main embodied NO_x emissions importers (main suppliers) networks of BTH; the red circle is the main embodied NO_x emissions importers (main suppliers) networks of BTH. Please refer to Table S1for the abbreviations of province names.

3.4. Emissions intensity analysis

Previous research (Zheng et al., 2019) found that carbon and water supply chains in the BTH urban agglomeration are both inefficient because cities with low efficiency undertake production activities for cities with higher efficiency. Reducing emissions intensity of industries is a core focus of improving the quality of the atmosphere. In order to verify whether there is a similar law of air pollution, we compared the NO_x emission intensity between production-oriented cities and consumer-oriented cities (Fig. 7).

We compared the NO_x emission intensity between production-oriented cities (embodied NO_x net inflow more than 0) and consumer-oriented cities (embodied NO_x net inflow less than 0) (Fig. 7). The average emission intensity of cities may be affected by the industrial structure, and it cannot fully reflect the differences in industrial technology. Therefore, this study not only compared the average emission intensity of cities but also that of the top three high-emissions sectors, i.e. metals smelting & pressing, nonmetal mineral products, and electricity & heat sectors (accounting for 73.6% in total production-based emission) to deeply analyze the efficiency characteristics of BTH urban agglomeration.

In Fig. 7, “inefficient supply chain” means that the embodied NOx emissions in the supply chains are transferred from cities with high efficiency (low intensity) to cities with low efficiency (high intensity) and the “efficient supply chain” is the opposite (Zheng et al., 2019). According to the average emission intensity (Fig. 7a), the emission intensity of production-oriented cities is significantly higher than the consumer-oriented cities. Specifically, 75% of embodied NO_x emissions in the supply chains are transferred from cities with low efficiency (high intensity) to cities with high efficiency (low intensity). Tangshan, Handan, and Zhangjiakou are the most dominant production-oriented cities in supply chains, contributing 40% of inefficient embodied NO_x flows. Their emission intensities are 1.87, 1.82 and 3.54 Mt/million yuan, respectively, which are 29%, 36% and 144% higher than the average value of the BTH region, respectively. In contrast to these production-oriented cities, Beijing, Tianjin, Baoding, and Cangzhou have higher production efficiencies, and their emission intensities are

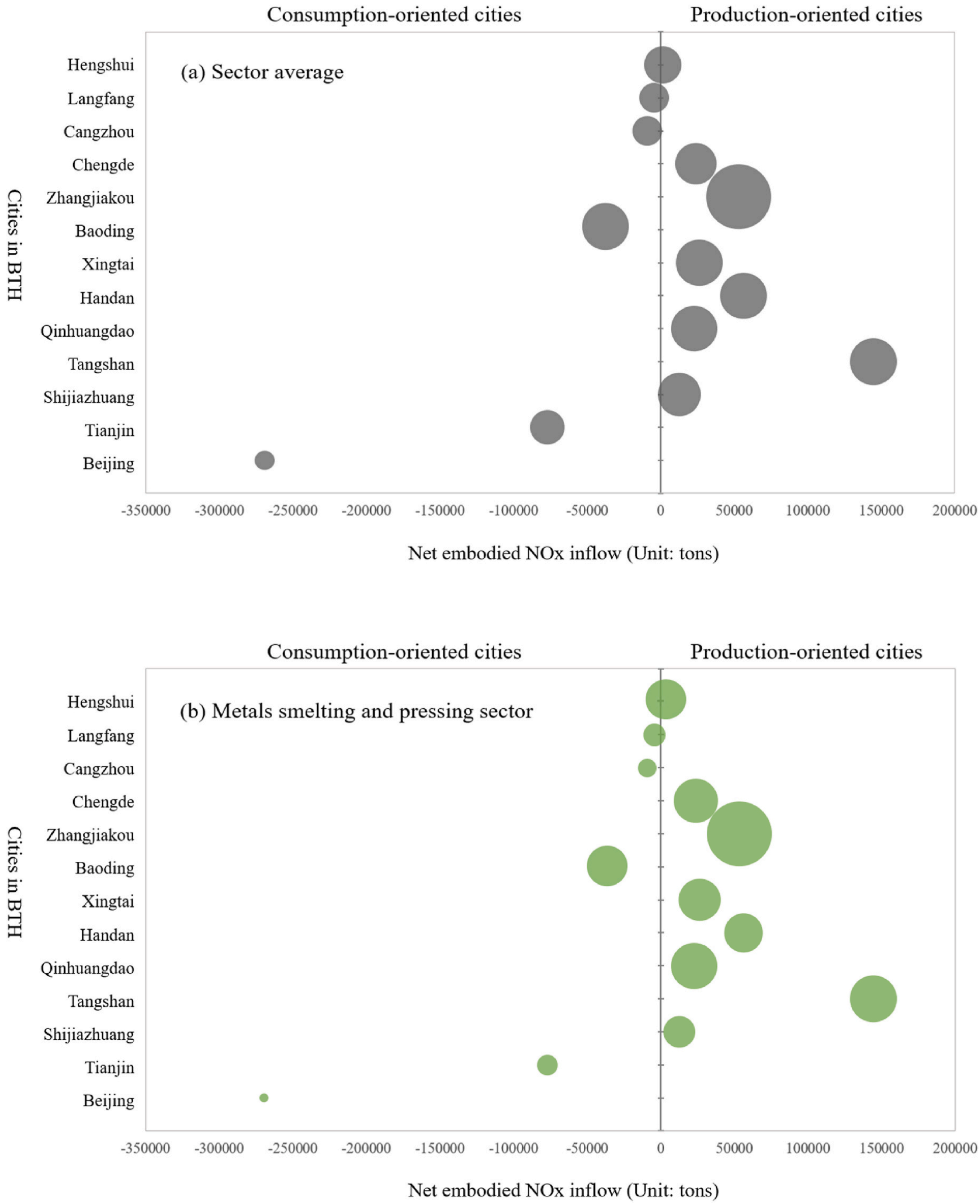
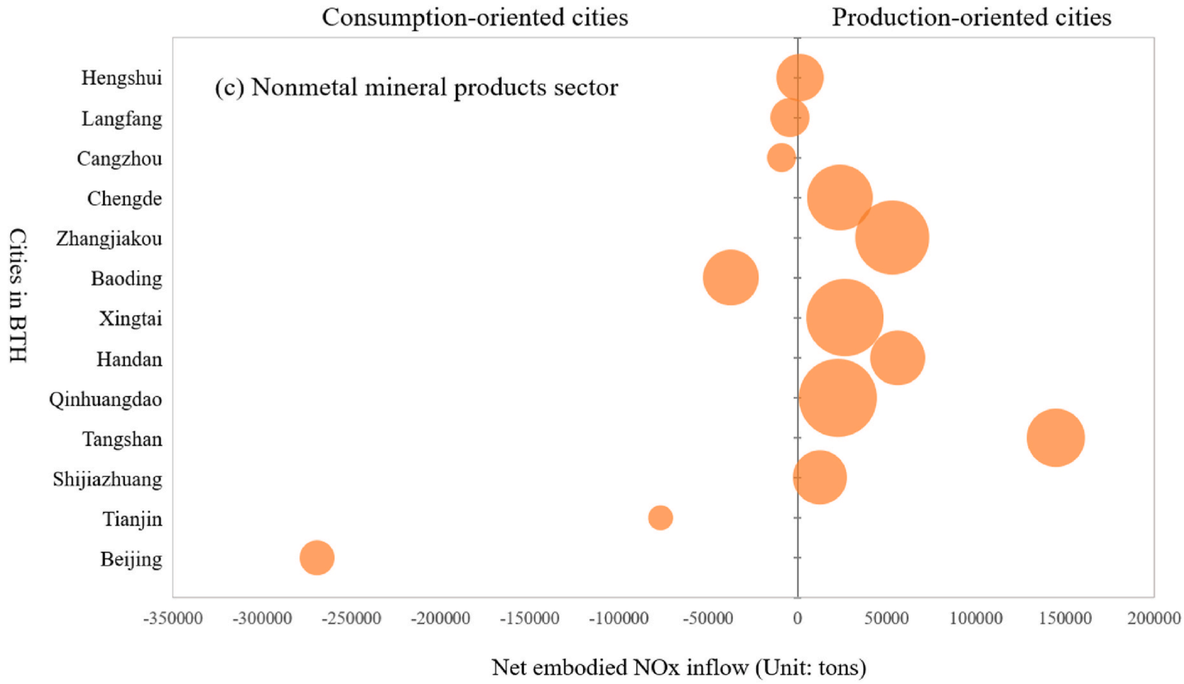


Fig. 7. Net embodied NO_x inflow and emission intensity in BTH.

48% lower than average in the BTH region. However, they outsource their production activities and import products to sustain their demand. Therefore, the inefficient supply chains increased the total NO_x emissions, thus aggravating regional air pollution.

From the perspective of the three top high emission sectors, the regional emission intensity gap between sectors is different. For the metals smelting and pressing sector and nonmetal mineral products sectors (Fig. 7b and c), there is a wider gap in emission intensity between production-oriented cities (1.03–4.43 Mt/million yuan) and consumer-oriented cities (0.08–0.45 Mt/million yuan), which leads to additional emissions of air pollutants. However, the emission intensity gap between production-oriented and consumer-oriented cities of the electricity & heat sector is relatively small (Fig. 7d).

The area of the circle represents the relative emission intensity of (a) sector average, (b) metals smelting and pressing sector, (c) nonmetal mineral products sector, and (d) electricity & heat sector (per production value NO_x emissions).



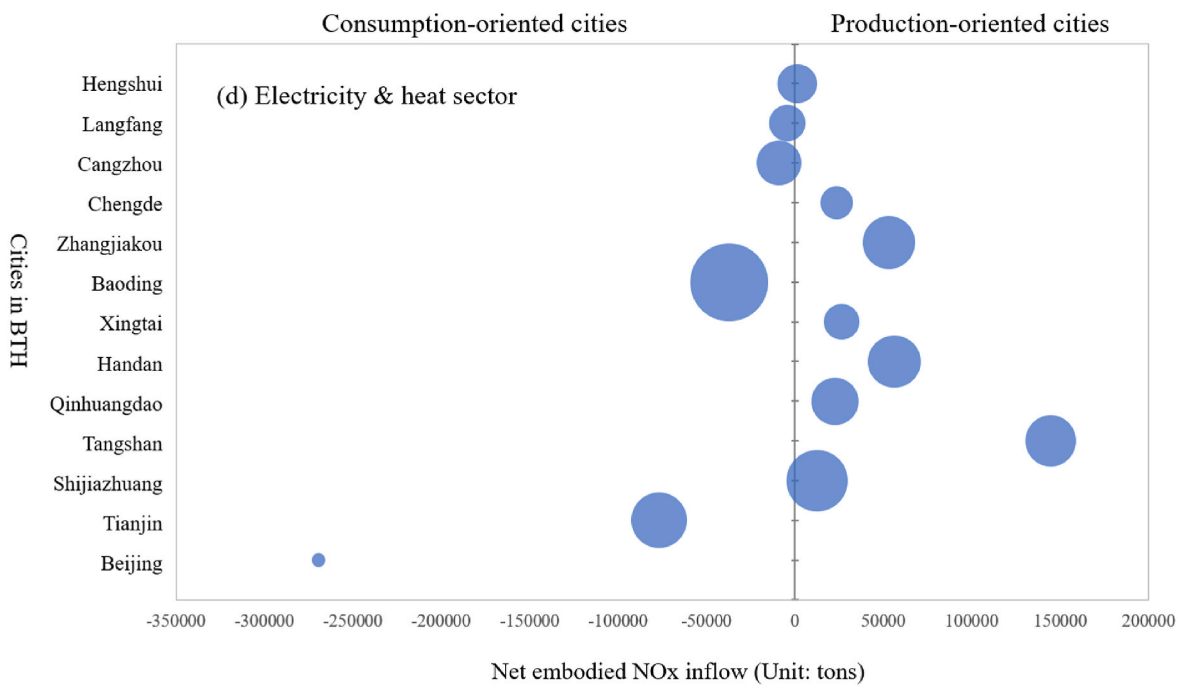


Fig. 7. (*continued*).

3.5. Analysis on the formation of consumption-driven emissions networks

We mapped the inter-city consumption-driven NO_x networks within the BTH region. Actually, the formation of three key consumption-driven NO_x networks is mainly affected by industrial layout. The land competition between the high added value industries and low value-added industries not only pushes up the land price, but also promotes the relocation and diffusion of low value-added industries (Chen et al., 2018). Thus, land price is undoubtedly an important indicator reflecting the influence of many factors of the industrial layout of urban agglomeration. Factor correlation analysis showed that there is the strongest positive correlation coefficient between land price and consumption emission in the BTH region (see Table 1). In addition, determinants of market demand, such as economic development level, population density, are found to have an impact on the land price (Hansen and Kristensen, 1991; Verburg et al., 1999). At the city level, the higher the level of land price, and the higher the level of consumption-based emissions. The price of land in Beijing is much higher than other cities, 5 to 10 times higher than other cities, which lead to excessive cost to build factories in Beijing. The value-added share of sectors which close to the consumer end (e.g. tertiary industries and construction sector) in their prices is usually much larger than that of basic industries (Suh, 2006).

Table 1
Factor correlation analysis.

City	Impact factors					Consumption-based NO_x emissions (tons)
	Population Density (person/km^2)	Land price (yuan/m^2)		Per Capita GDP (yuan)	Proportion of tertiary industry	
		Average price	Industrial land			
BJ	1261	9080	1569	87,475	76.50%	458595.05
TJ	845	5205	780	93,173	47.00%	398765.46
SJZ	718	1857	671	43,330	73.56%	214572.21
TS	569	1465	519	76,438	35.64%	176327.90
QHD	387	1697	364	37,708	60.71%	41233.93
HD	769	1111	605	32,567	45.38%	129934.69
XT	580	1020	555	21,312	39.57%	68466.11
BD	513	1360	537	23,970	32.53%	121274.24
ZJK	119	1014	401	28,075	45.63%	64157.45
CD	89	776	360	33,708	39.43%	33289.17
CZ	517	900	370	38,825	47.51%	78533.40
LF	691	1750	387	40,419	55.27%	46822.83
HS	498	912	385	23,034	32.29%	34228.94
Pearson Correlation	0.797[a]	0.906[a]	0.889[a]	0.867[a]	0.506[a]	–

[a] Correlation is significant at the 0.01 level (2-tailed).

Under the price control, steel, cement, and electricity factories usually choose cities with a low land price. Land in Beijing is given priority for the development of high-value-added tertiary industries. The economically developed and densely populated city/region outsource low added value and high pollution production activities to sustain their demand. However, if the technology is not synchronized outsourced, it will lead to low efficiency, which results in the pollution paradise hypothesis effect. Therefore, the simultaneous transfer of production and technology is crucial for the overall reduction of pollutant emissions in the BTH region.

The data in the table is from The National Environmental Yearbook 2017 (National Bureau of Statistics of China, 2018).

4. Conclusion and policy implications

The purpose of this paper is to quantitatively unveil the consumption-driven NO_x networks among cities and enhance the understanding of the contradiction between the economy and environment. We further identified the structural and functional differences at two scales of city and urban agglomeration. We found there is a significant imbalance and inefficient in the environment and economic system of the BTH region.

From the perspective of the city scale, we revealed consumption-driven NO_x networks related to BTH. The embodied transfer networks in BTH are inefficient and highly polluting, especially in the non-electricity sectors, where the emission intensity of production-oriented cities is significantly higher than that of consumer-oriented cities. Among the three top high emission sectors, metal products and equipment manufacturing sectors consumption-driven NO_x network is most inefficient. Under the existing industrial layout, the production and consumption roles of cities will not change in the short term, so it is critical to improve emission reduction technologies in production-oriented cities, especially for metals smelting and pressing sector.

From the national scope, the results indicate that taking the BTH region as an object of reference, there are obvious regional differences in consumption-driven NO_x networks of north and south. The northern provinces emitted a lot of pollutants for BTH's consumption, at the same time, the BTH region also emitted pollutants due to supply intermediate products for the east and south provinces in China. This will cause great pressure on the further emission reduction of the BTH region in the future.

Therefore, if we do not consider the regularity of the economic system itself, just stopping production and limiting production to protect the environment may have a great impact on the economy. In the long run, the policy of stopping production and limiting production is also unsustainable. This requires policy-makers to take into account the regional compensation and cooperation mechanism. First of all, in the BTH urban agglomeration, the distribution of consumption and production roles in Beijing, Tianjin and Hebei is largely related to industrial layout. Industrial layout is affected by land prices to a certain extent. We cannot locate factories in densely populated areas with high land prices. Therefore, the concept of common responsibility for the atmospheric environment of BTH urban agglomeration should be established. Consumer-oriented cities should provide production-oriented cities financial and technical support to help them accomplish the task of reducing emission intensity to achieve the reduction of total pollution emissions in the BTH.

Secondly, from a national perspective, the BTH urban agglomeration as a whole needs to have a new position on its role. The BTH is a bridge between southeast coastal provinces and northern provinces for pollutant transfer. The BTH is a vital part of China's supply chain, a bond to balance the economic environment imbalance between the north and south of China. The BTH region should not only establish financial and technical cooperation with developed coastal provinces in southeast China to achieve industrial optimization and emission reduction, but also help the coal and energy industries in northern China to upgrade production and emission reduction technologies. This is an effective way to reduce China's overall air pollution emissions through the supply chain.

From the perspective of academic research, there are some uncertainties are from the MRIO table and NO_x emissions data of city-level. The uncertainty analysis of the MRIO table has been discussed by many scholars, but it is still a very practical tool to analyze macroeconomic and environmental systems. In addition, the 2017 input-output table updated based on the ANAIS model also has uncertainties. We used the emissions data from the government environmental statistics data under a regular sampling survey system. The limitation is that government publishes emission statistics has a time lag. This article did not apply the latest year data, because the latest authoritative official emissions data of cities and industries in China are not available for the public. We may assume the emission linkages of cities may be stable in a few years. Generally, without the influence of sudden policies, the industrial structure of a region will not change significantly in three to four years. According to China's latest economic statistics, the proportion of the industries structures in the BTH region has little change from 2017 to 2020 (Please see Table S7-10). Therefore, the data of this study are time-valid. However, in the future, new regular changes may be observed when new data becomes available. This study mainly provides a new research perspective to re-examine the driving mechanism of pollution, and provides a quantitative calculation method for the establishment of the refined regional cooperative pollution control model and responsibility-sharing system.

Credit Author Statement

Yun Sun: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft preparation, **Yuan Wang:** Conceptualization, Writing – review & editing, Validation, Funding acquisition, **Zengkai Zhang:** Methodology, Software, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2022.114601.

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