6482 words

Abstract

China's air pollution policies prioritize city heterogeneity, and launch the one-city-one-policy framework. Production fragmentation extends air pollution policies beyond the local scale. Therefore, air pollution needs to be controlled in coordination between cities rather than individually, considering the pollution embodied in supply chains. We illustrate the embodied NO_x in supply chains and its transfer patterns in the highly polluted Beijing-Tianjin-Hebei (BTH) urban agglomeration in China, with a city-level multiregional input-output (MRIO) model in 2012. The results indicate that Tangshan and Beijing are BTH cities with the highest production- and consumption-based NO_x emissions, respectively. The electricity and heat, metal, and nonmetal sectors are the main suppliers in the NO_x supply chains. The critical supply chain paths largely terminate at the final demand of the construction sector in Beijing, Tianjin, Baoding and Shijiazhuang and the equipment manufacturing sector in southeastern Chinese provinces. Despite industry heterogeneity, the NO_x transfer pattern between BTH cities is generally efficient, extending from low- to high-emission intensity cities, while the pattern between BTH cities and other provinces is the opposite. The results reveal the city-level emission reduction potential. The emission intensities of BTH production-oriented cities should be reduced because the transfer of polluting enterprises to southeastern coastal areas is unrealistic. Financial incentives can be offered to enterprises purchasing products from low-emission intensity enterprises. It is an effective measure to establish a capital and technical cooperation system between key supply chains node cities, such as Tangshan and its major steel product consumption regions.

Keywords

Beijing-Tianjin-Hebei urban agglomeration; Embodied NO_x emissions; Multiregional input-output model; Structural path analysis; Supply chain

1. Introduction

China has suffered serious air pollution (mainly $PM_{2.5}$ and O_3) in recent years (Miao et al., 2020). The 14th Five-Year Plan of China emphasizes NO_x control as a key step in reducing $PM_{2.5}$ and O_3 levels (Sillman et al., 1990; The Central Committee of the Communist Party of China, 2020). The Beijing-Tianjin-Hebei (BTH) urban agglomeration is one of the most populated regions in China, accounting for 8.5% of the population and 8% of the gross domestic product (GDP). Moreover, BTH urban agglomeration experiences the most severe air pollution. Cities in the BTH typically exhibit nearly twice as many days per month with the air quality exceeding various standards such as the national average. This urban agglomeration has attracted attention from quite a number of environmental scientists on carbon emission, air pollution and resources efficiency (Bai et al., 2021; Liu et al., 2021; Wang et al., 2019). At present, to control air pollution, a large number of measures has been implemented, including the closure of factories not satisfying emission standards (Ministry of Ecology and Environment of PRC, 2019), promotion of the installation of desulfurization, denitration and dust removal (Ministry of Ecology and Environment of PRC, 2014), and application of ultralow emissions standards in steel industries (Ministry of Ecology and Environment of PRC, 2017a). China has invested 900 million dollars in air pollution control in BTH and surrounding areas, accounting for approximately 24% of the total national investment in air pollution control (Wen, 2015). The proportion of days with air quality below national standards in BTH decreased from 62.5% in 2013 to 47.6% in 2015, but this figure remained as high as 46.9% in 2019 (Ministry of Ecology and Environment of PRC, 2020). After industrial upgrading in many cities, highly polluting factories were relocated to other cities. This phenomenon may lead to the realization of the pollution paradise hypothesis (Feng et al., 2020). Current air prevention and control measures are aimed at local air pollution prevention and control, thus ignoring external influences through supply chains. Because of the spillover effects of pollution, nonlocal production and consumption activities also affect the air quality in BTH (Wang et al., 2020; Zheng and Xu, 2020). Therefore, it is necessary to consider any spillover effects on air pollution policies from the supply chain perspective. The latest atmospheric pollution policy also emphasizes collaborative efforts across administrative boundaries to achieve emission control and pollution prevention (Ministry of Ecology and Environment of PRC, 2018).

Thus, it is not enough to reduce emissions only from the perspective of production, whereas emission reduction along the whole supply chain is the key to air pollution reduction. To investigate the transfer of pollutants through supply chains, the input-output (IO) technique has been widely employed to study embodied emissions (Huo et al., 2014; Lenzen, 1998). Linkages between sectors (He et al., 2017), provinces (Zhao et al., 2016), and regional industries (Wang et al., 2017; Yang et al., 2018) of emissions in China have been well discussed in existing studies. In BTH, they found that air pollutant emissions were transferred from the nonmetal product sector in Hebei province to the construction sector in Beijing in 2010 (Wang et al., 2017) and most of the BTH embodied emissions in exports was transferred to neighboring provinces and developed east coastal regions in China (Zhao et al., 2016). Across China, Yang et al. (2018) investigated the transfer of embodied $PM_{2.5}$ emissions to and from the North China region and reported that Beijing and Tianjin largely transferred embodied pollution to Hebei and Shanxi provinces, while Jiangsu, Shanghai, and Zhejiang provinces tended to import embodied air pollutants from Shandong and Henan provinces. The impact of supply chains on the atmospheric environment can be evaluated according to the amounts of pollutants it emits (Feng et al., 2020; Wang et al., 2018) and their results showed that the supply chain has different impacts on emissions in different regions. Structural path analysis (SPA) based on MRIO models provide more specific directions for supply-side and demand-side measures on air pollution control (Qi et al., 2019; Zheng and Xu, 2020). Zheng and Xu (2020) identify critical sectors and $PM_{2.5}$ emission flows through whole supply chains across 30 provinces in China in 2012.

The above studies focus on inter-regional and sectoral linkages of air pollutant emissions at the provincial level. However, there exists a gap in the existing body of knowledge, i.e., previous studies have focused on Hebei province but have ignored the heterogeneity in its 11 cities, such as the industrial structure, city size, and development degree. Any results dependent on the city-level resolution may differ from those dependent on the province-level resolution. Currently, there are some Beijing-Tianjin-Hebei city-level studies, but mostly on energy, carbon and water footprints (Li et al., 2019; Zhang et al., 2021; Zheng et al., 2021; Zheng et al., 2019b). However, there are few studies on air pollutants between cities. In addition, industrial emission linkages between cities should also be taken into account in the one-city-one-policy framework. Examination of the transfer of embodied air pollution at the city level may provide a scientific basis for the formulation of air pollution management policies within the one-city-one-policy framework and help identify key cities to achieve collaborative emission reduction.

To bridge the above gap, this paper presents the NO_x emission flows embodied in intercity supply chains considering all 13 cities in BTH in 2012 with the city-level multiregional input-output (MRIO) model and structural path analysis (SPA) method. We examine NO_x patterns from both producer and consumer perspectives, as well as the critical supply chain paths among BTH cities and those with other provinces. This study aims to better understand the interregional and sectoral linkages of NO_x emissions and identifies critical cities, sectors and supply chain paths. The results may provide a basis of intercity economic correlation for one-city-one-policy, which will help to balance pollution reduction and economic development.

2. Data Sources and Methodology

2.1. Environmental Extended MRIO Analysis of BTH Cities

The input-output (IO) analysis, developed by Wassile Leontief, has been commonly adopted to estimate the macroeconomic impacts of industries within the national or regional economy (Leontief, 1970). IO analysis describes, through symmetrical tables, the interdependencies between activity sectors within an economy (Miller and Blair, 2009). The multiregional input-output (MRIO) model is one kind of IO model. MRIO tables exhibit a similar structure to that of IO tables, but inter- and intraregional transactions are considered, and it is possible to identify the trade occurring between sector *i* in region *r* and sector *j* in region *s*. Therefore, MRIO tables provide a suitable method to analyze the interconnections among both sectors and regions (Wang et al., 2017).

IO tables can be divided into two main components: the transaction matrix and the final demand. The transaction matrix describes the flows from sector *i* in region *r* to sector *j* in region *s*. The MRIO model is constructed based on the connections in the associated MRIO tables. The fundamental equation of the IO model is (Leontief, 1970):

$$\boldsymbol{Q} = \boldsymbol{L}\boldsymbol{Y} = (\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{Y} \tag{1}$$

This model is also referred to as the Leontief MRIO model, where matrix $\boldsymbol{Q}$ expresses the total output, $\boldsymbol{Y}$ is the final demand matrix (including export), matrix $\boldsymbol{A}$ is the direct-input coefficient matrix, and $(\boldsymbol{I} - \boldsymbol{A})^{-1}$ is the Leontief inverse matrix $\boldsymbol{L}$, or the multiplier matrix, which expresses the total production in each sector required to satisfy the final demand.

$$\boldsymbol{Z} = \begin{bmatrix} z_{11}^{11} & \cdots & z_{1j}^{1s} \\ \vdots & \ddots & \vdots \\ z_{i1}^{r1} & \cdots & z_{ij}^{rs} \end{bmatrix};\ \boldsymbol{A} = \begin{bmatrix} a_{11}^{11} & \cdots & a_{1j}^{1s} \\ \vdots & \ddots & \vdots \\ a_{i1}^{r1} & \cdots & a_{ij}^{rs} \end{bmatrix};\ a_{ij}^{rs} = \frac{z_{ij}^{rs}}{q_j^s} \tag{2}$$

where Z_{ij}^{rs} denotes the intermediate products transferred from sector *i* in region *r* to sector *j* in region s (unit: yuan), 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*.

The supply-side IO model was developed by Ghosh (Ghosh, 1958) as a supplement to the Leontief demand-driven IO model.

$$\boldsymbol{w} = \boldsymbol{vG} = \boldsymbol{v}(\boldsymbol{I} - \boldsymbol{B})^{-1} \tag{3}$$

The model is also referred to as the Ghosh model, where $\boldsymbol{w}$ is the total input vector, $\boldsymbol{v}$ is the primary input vector, matrix $\boldsymbol{B}$ is the direct-output coefficient matrix, and $(\boldsymbol{I} - \boldsymbol{B})^{-1}$ is the Ghosh inverse matrix describing both the direct and indirect intersectoral relationships of the outputs and unitary primary inputs (Miller and Blair, 2009).

$$\boldsymbol{B} = \begin{bmatrix} b_{11}^{11} & \cdots & b_{1j}^{1s} \\ \vdots & \ddots & \vdots \\ b_{i1}^{r1} & \cdots & b_{ij}^{rs} \end{bmatrix};\ b_{ij}^{rs} = \frac{z_{ij}^{rs}}{q_i^r} \tag{4}$$

where b_{ij}^{rs} denotes the proportion of direct input value of product or service from sector *i* in region *r* to sector *j* in region *s* to the total output of sector *i* in region *r*.

Production-based emissions are the direct emissions in a given region. Consumption-based emissions denote the emissions generated by the local final demand, i.e., the amount of embodied emissions involved in the intermediate production flows along production supply chains in addition to the consumers of these products (Huo et al., 2014; Qian et al., 2022). Environmentally extended input-output (EEIO) analysis has been widely implemented (Lenzen, 1998, Huo et al., 2014, Wang et al., 2017, Yang et al., 2018). To include any extension, either environmental or social, we must consider an additional matrix or vector that provides the amounts of pollutants. Incorporating this vector into Equation (1), we obtain the expression of consumption-based NO_x emissions as:

$$\boldsymbol{E} = \boldsymbol{p}(\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{Y} \tag{5}$$

where $\boldsymbol{E}$ denotes the consumption-based NO_x emissions (unit: ton), $\boldsymbol{p}$ is a vector whose elements are defined as the amount of the direct NO_x emissions per unit total output (unit: ton/yuan), $(\boldsymbol{I}-\boldsymbol{A})^{-1}$ is the Leontief inverse matrix, and $\boldsymbol{Y}$ is the final consumption.

The embodied NO_x transferred from sector i in region r to sector j in region s can be expressed as (Wang et al., 2017):

$$e_{ij}^{rs}=p_i^r\times l_{ij}^{rs}\times y_j^{ss} \quad (6)$$

where e_{ij}^{rs} denotes the embodied pollutants transferred from sector i in region r to sector j in region s (unit: ton), p_r^i is the direct emission intensity of air pollutants of sector i in region r (unit: ton/yuan), l_{ij}^{rs} is the total demand coefficient for sector j in region s to satisfy one unit of final demand products of sector i in region r, which is an element of the Leontief inverse matrix, and y_j^{ss} denotes the final demand products of sector j in region s for itself (unit: yuan).

In this paper, a bottom-up methodology is applied in city-level MRIO table compilation based on partial-survey methods to study the interregional and sectoral linkages among cities (Zheng et al., 2019a). The table contains 26 economic sectors and 41 regions, including 11 cities in Hebei province and 26 other provinces and municipalities directly under the Central Government (i.e., Beijing, Tianjin, Shanghai, and Chongqing) in China (excluding Taiwan, Hong Kong, and Macao due to data availability). In the following text, Chongqing, Shanghai and 26 provinces are referred to as the other 28 provinces for convenience of description. The gravity model was employed to estimate the intercity trade flow. The RAS approach can be applied to adjust the trade flow matrix to ensure agreement with the sum constraints (Jackson and Murray, 2004; Mi et al., 2017; Zheng et al., 2019a; Zheng et al., 2019b). Under the assumption of identical trade coefficients between city- and province-level MRIO tables, city-level MRIO tables modified with the RAS approach are nested in the 2012 provincial-level China MRIO table. The assumption of identical trade coefficients suggests that the inflows (outflows) of the sectors in the 11 Hebei cities are distributed to other provinces and megacities at the same proportion as that of the Hebei province inflows (outflows) of these sectors (please refer to the Supporting Information for details).

2.2. Structural Path Analysis

Defourny and Thorbecke (1984) were the first to propose the SPA methodology (Defourny and Thorbecke, 1984). SPA tracks the flows of commodities and the associated environmental pressure within the supply chain network and identifies critical supply chain paths inducing environmental pressures (Qi et al., 2019). SPA can be conducted based on MRIO models. SPA unravels the Leontief inverse matrix $(\boldsymbol{I}-\boldsymbol{A})^{-1}$ and the Ghosh inverse matrix $(\boldsymbol{I}-\boldsymbol{B})^{-1}$ via Taylor expansion.

$$(\boldsymbol{I}-\boldsymbol{A})^{-1}=\boldsymbol{I}+\boldsymbol{A}+\boldsymbol{A}^2+\boldsymbol{A}^3+\cdots+\boldsymbol{A}^n,\ \lim_{n\to\infty}(\boldsymbol{A}^n)=0 \tag{7}$$

$$(\boldsymbol{I}-\boldsymbol{B})^{-1}=\boldsymbol{I}+\boldsymbol{B}+\boldsymbol{B}^2+\boldsymbol{B}^3+\cdots+\boldsymbol{B}^n,\ \lim_{n\to\infty}(\boldsymbol{B}^n)=0 \tag{8}$$

This study integrated SPA into the city-level MRIO model to extract individual supply chain paths according to the Leontief and Ghosh MRIO models. The supply chain path in the Leontief MRIO model describes the environmental pressure of the starting region sector incrementally driven by the final consumption of products originating from the ending region sector (Equation 9). The supply chain path in the Ghosh MRIO model suggests that the environmental pressure of the ending region sector is cumulatively caused by the primary inputs of the starting region sector (Equation 10) (Qi et al., 2019).

$$NOx\ emissions=\boldsymbol{p}(\boldsymbol{I}+\boldsymbol{A}+\boldsymbol{A}^2+\cdots+\boldsymbol{A}^n)diag(\boldsymbol{y_n})$$
$$=\boldsymbol{pI}diag(\boldsymbol{y_n})+\boldsymbol{pA}diag(\boldsymbol{y_n})+\boldsymbol{pA}^2diag(\boldsymbol{y_n})+\cdots+\boldsymbol{pA}^ndiag(\boldsymbol{y_n}) \tag{9}$$

$$NOx\ emissions=diag(\boldsymbol{v_n})(\boldsymbol{I}+\boldsymbol{B}+\boldsymbol{B}^2+\cdots+B^n)P'$$
$$=diag(\boldsymbol{v_n})\boldsymbol{Ip'}+diag(\boldsymbol{v_n})\boldsymbol{Bp'}+diag(\boldsymbol{v_n})\boldsymbol{B}^2\boldsymbol{p'}+\cdots+diag(\boldsymbol{v_n})\boldsymbol{B}^n\boldsymbol{p'} \tag{10}$$

where $\boldsymbol{p'}$ denotes the transposition of sector $\boldsymbol{p}$, vector $\boldsymbol{y_n}$ denotes the final demand of region *n*, vector $\boldsymbol{v_n}$ denotes the primary inputs of region n, and the *diag* notation denotes vector diagonalization.

2.3. Data Source

The case study area was the BTH urban agglomeration (Figure S1), including Beijing, Tianjin, and 11 cities in Hebei province. City and province abbreviations are listed in Table S1. To reveal the transfer patterns of embodied pollutant emission flows at the city level, the 2012 city-level MRIO table was retrieved from China Emission Accounts and Datasets (CEADs) (China Emission Accounts & Datasets, 2021), which describes the intermediate trade flows among 13 cities in BTH and 28 provinces. To fit our study, the MRIO table was modified into 26 sectors (please refer to Table S2). A NO_x emissions inventory was compiled, which contained the NO_x emissions originating from 26 sectors in 13 cities across BTH and 28 other provinces in China (please refer to Table S5). Provincial NO_x emission data were obtained from the 2012 National Environmental Statistical Yearbook (National Bureau of Statistics of China, 2013). Emissions for each sector in each province are estimated according to Equation S1.

City-level NO_x emission data pertaining to various industrial sectors were acquired from the official environmental statistics emission database, which was aggregated considering 12929 industrial enterprises in BTH (Figure S2 and Table S4). City-level NO_x emission data of nonindustrial sectors were estimated based on the national average emission intensity of primary energy consumption and the primary energy consumption level (not including electricity) of each sector (Ministry of Ecology and Environment of PRC, 2017b).

$$E_c^{n\prime} = P_{n\prime} \times W_c^{n\prime} \tag{11}$$

where $E_c^{n\prime}$ denotes the NO_x emissions of nonindustrial sector n in BTH city c (unit: ton), $P_{n\prime}$ denotes the national average NO_x emission intensity of primary energy consumption of nonindustrial sector n (unit: ton/tce), and $W_c^{n\prime}$ denotes the primary energy consumption (not including electricity) of nonindustrial sector n in BTH city c (unit: tce).

3. Results

3.1. Production- and Consumption-Based NO_x Emissions from the City and Sector Perspectives

The production- and consumption-based NO_x emissions of BTH are roughly equal (15.09 Mt). According to Equation (5), the cities in BTH can be divided into production-oriented cities (production-based emissions > consumption-based emissions, i.e., with net NO_x emissions inflows lower than 0) and consumption-oriented cities (consumption-based emissions > production-based emissions, i.e., with net NO_x emissions inflows higher than 0) (please refer to Figure 1). Due to their large population and high quality of life, Beijing and Tianjin exhibit the highest consumption-based emissions in BTH, accounting for approximately 36.92% (5.57 Mt) of the overall consumption-based emissions of BTH. However, the difference between Beijing and Tianjin is that the consumption-based emissions of Beijing are 109% higher than its production-based emissions, while the consumption-based emissions of Tianjin are only 13% higher than its production-based emissions. This suggests that Tianjin is a city with both high production- and consumption-based emissions, while Beijing is a city mostly dominated by consumption-based emissions. Hebei province, as a whole, is a production-oriented province. However, Baoding, Langfang and Cangzhou are consumption-oriented cities in Hebei province. Tangshan is the largest production-oriented city, followed by Zhangjiakou, Shijiazhuang and Handan. The production- and consumption-based NO_x emissions of Chengde and Hengshui are roughly equal. Therefore, BTH is a very special region. Cities at different industrial development stages and with varying roles of industrial division occur in the same region. Therefore, it is necessary to study the region at the city level.

At the sectoral level, electricity and heat is the sector with the highest production-based emissions (9.13 Mt, 60.50%), followed by the metal (1.96 Mt, 13.00%), transportation and warehousing (1.48 Mt, 9.81%), and nonmetal mineral (1.19 Mt, 7.84%) sectors.

The electricity and heat sector is the leading production-based emission sector in all BTH cities (22-82%). The transportation and warehousing sector is the major production-based emission sector in consumption-oriented cities such as Beijing (0.54 Mt, 41.19%) and Tianjin (0.30 Mt, 12.03%). The metal and nonmetal sectors are the major production-based emission sectors in production-oriented cities. For example, the metal sector is the second largest emission sector in Tangshan (0.83 Mt, 29.55%) and Handan (0.38 Mt, 23.00%), and the nonmetal sector is the second largest emission sector in Shijiazhuang (0.25 Mt, 12.52%) and Xingtai (0.23 Mt, 28.92%).

There are also notable differences between the production- and consumption-oriented cities in terms of their consumption-based NO_x emissions. In production-oriented cities such as Tangshan, Zhangjiakou and Handan, the major consumption-based emission sectors include the electricity and heat, metal and nonmetal sectors. In consumption-oriented cities, such as Beijing, Tianjin, and Baoding, the construction, other industry, and equipment manufacturing sectors account for a large proportion of the associated consumption-based emissions. The construction sector is the largest sector contributing to the consumption-based NO_x emissions of Baoding (0.22 Mt, 24.19%) and is the second largest sector in Beijing (0.63 Mt, 26.33%).

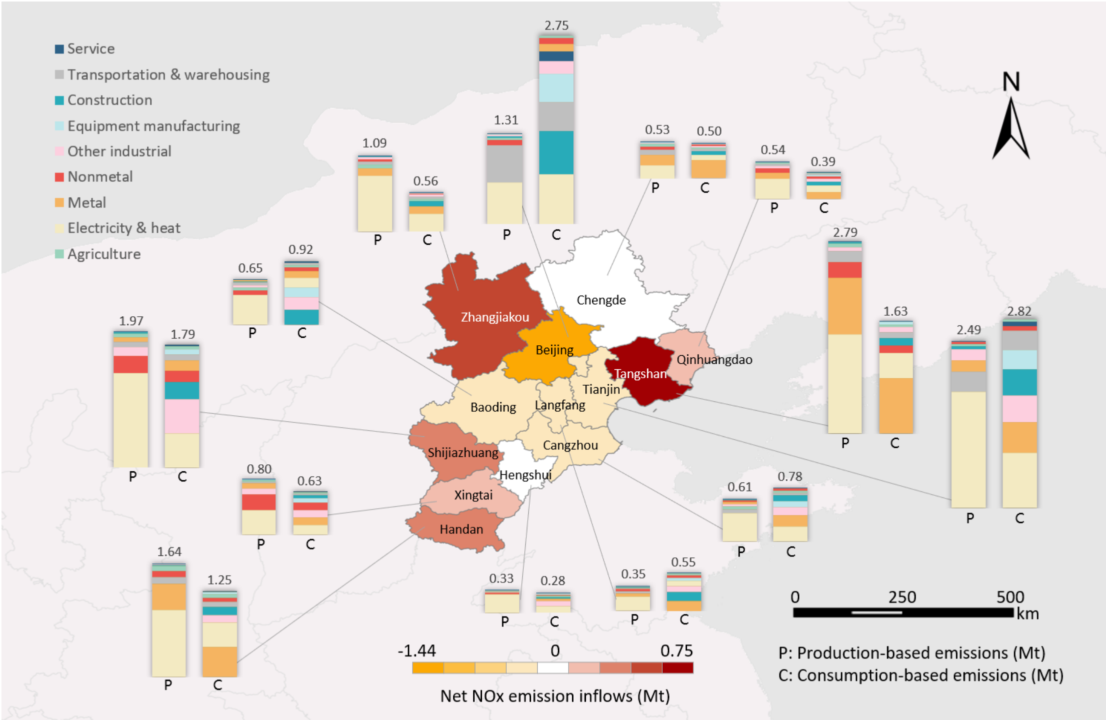
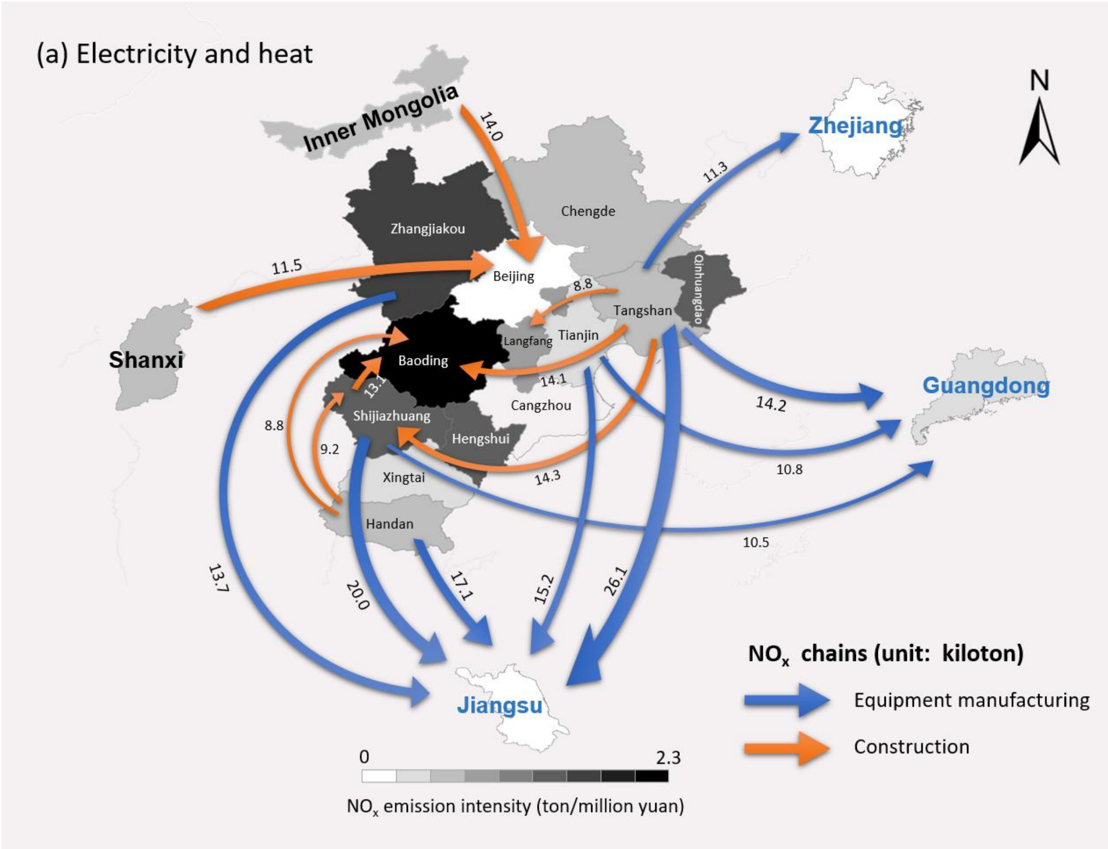


Figure 1. Production- and consumption-based NO_x emissions of the 13 cities in BTH (unit: Mt).

To obtain a more concise and intuitive overview, 26 sectors were merged into 9 sectors: agriculture, electricity and heat, metal, nonmetal, other industrial, equipment manufacturing, construction, transportation and warehousing, and service (please refer to Table S3).

3.2. Key Sector Linkage Networks of NO_x Emissions

The sector linkage is defined as the relationship between a given sector and other sectors of the economy through the direct or indirect purchase and sales of commodities (Miller and Lahr, 2001). According to the above research, the electricity and heat, metal, and nonmetal sectors are the main suppliers in the NO_x supply chains. Intercity-sector linkages of the embodied NO_x emissions can be measured according to the city-level MRIO table based on Equation (6). In addition, the obtained spatial expression facilitates analysis of the emission responsibility between cities. The results indicate that there are three key intercity-sector linkage supply chain networks: (a) the electricity and heat supply chain network, (b) the metal supply chain network, and (c) the nonmetal supply chain network (as shown in Figure 2).



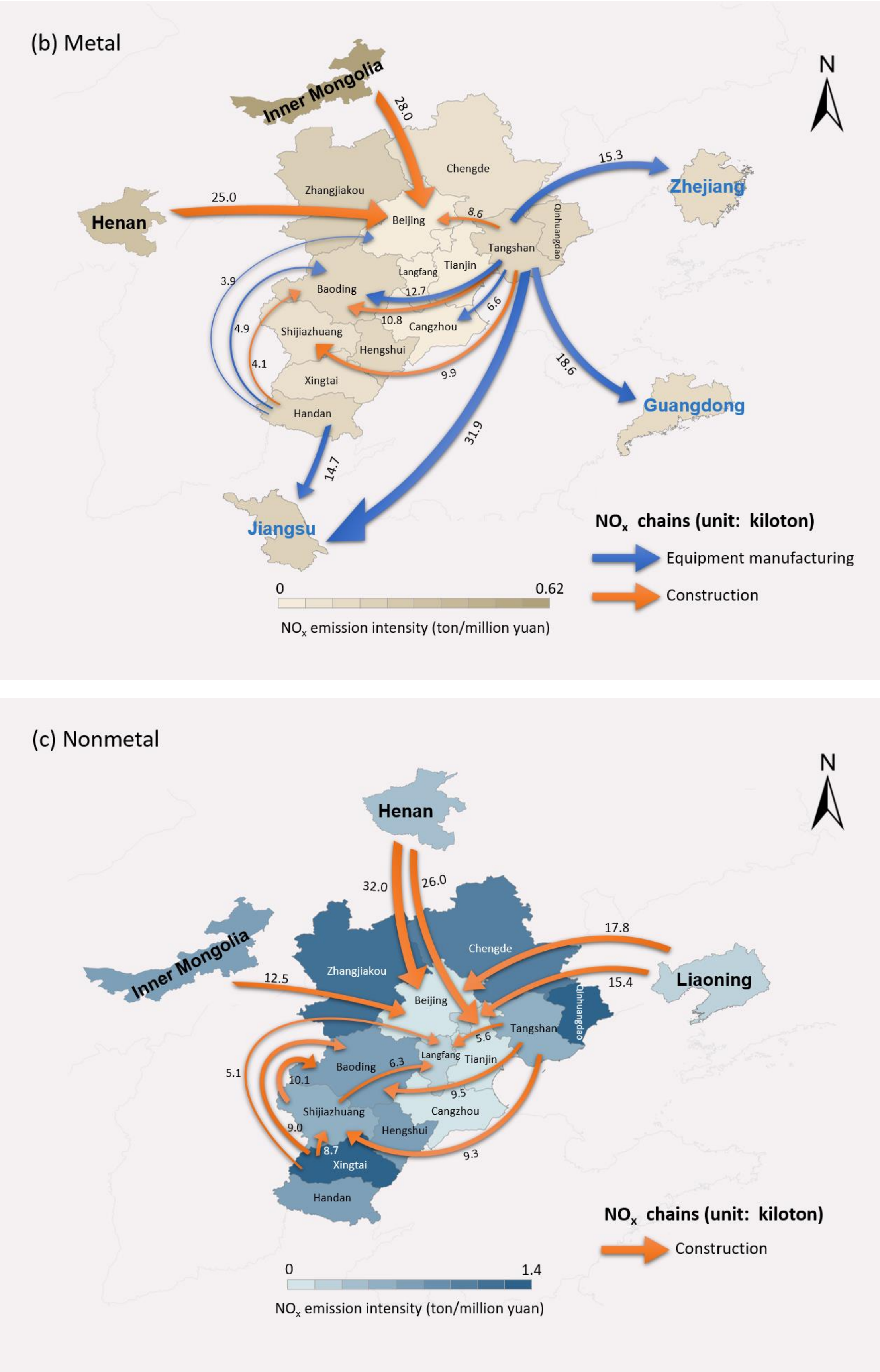


Figure 2. Main supply chains among BTH and other provinces.

Major embodied NO_x flows from the direct NO_x emitters ((a) electricity and heat sector, (b) metal sector and (c) nonmetal sector) to the final consumers. The width of the arrows in the figure indicates the magnitude of the NO_x transfer flows. The color of the arrows indicates the final consumption sectors. The colors of the regions indicate the NO_x emission intensities of the (a) electricity and heat sector, (b) metal sector and (c) nonmetal sector.

NO_x transfer is largely driven by the demand of the final consumer sectors of cities. The main electricity and heat consumer in BTH is the construction sector in Beijing, Baoding and Shijiazhuang. Specifically, the electricity and heat consumption of the construction sector in Beijing mainly originates from Inner Mongolia (14.0 kilotons) and Shanxi (11.5 kilotons), both outside BTH. However, the construction sector in Baoding and Shijiazhuang imports electricity and heat from cities in Hebei province, such as Handan, Tangshan and Shijiazhuang. The flows originating from the electricity and heat sector in BTH to provinces outside terminate at the equipment manufacturing sector in southeastern coastal provinces (Zhejiang, Jiangsu and Guangdong).

We also find that in the BTH region, electricity and heat are transferred from low-emission to high-emission intensity cities, and the electricity and heat supply chain network is efficient. This kind of supply chain could reduce pollutant emissions (Table 1). For example, Tangshan supplies electricity and heat to the construction sector in Baoding. If the supplied electricity and heat were locally produced in Baoding, 44.44 kilotons of NO_x would be emitted. However, since the emission intensity of Tangshan is lower than that of Baoding, the electricity and heat produced in Tangshan cause the emission of only 14.11 kilotons of NO_x. Therefore, due to the occurrence of this supply chain, the NO_x emissions of the BTH region are reduced by 30.32 kilotons. This kind of supply chain layout efficiently reduces pollutants.

Table 1. Balance of the avoided emissions of the electricity and heat supply chain

network in BTH (unit: kiloton)

Supply chain		Emissions from nonlocal production	Emissions from local production	Balance of the avoided emissions
From	To			
Tangshan (electricity and heat)	Shijiazhuang (construction)	14.30	28.47	-14.17
Tangshan (electricity and heat)	Baoding (construction)	14.11	44.44	-30.32
Shijiazhuang (electricity and heat)	Baoding (construction)	13.08	20.69	-7.61
Handan (electricity and heat)	Shijiazhuang (construction)	9.17	19.02	-9.86
Handan (electricity and heat)	Baoding (construction)	8.84	29.01	-20.18
Tangshan (electricity and heat)	Langfang (construction)	8.84	12.72	-3.88

However, in regard to the supply chains between BTH cities and other provinces, the emission intensity of the electricity and heat sector in the electricity and heat-consuming regions is lower than that of the electricity and heat sector in the producing regions, which leads to supply chain network inefficiency (Table 2). For example, Tangshan supplies electricity and heat to the Jiangsu equipment manufacturing sector. If these supplied products were locally produced in Jiangsu province, only 5.74 kilotons of NO_x would be emitted. However, since the emission intensity of Tangshan is higher than that of Jiangsu, the electricity and heat manufactured in Tangshan are associated with NO_x emissions of 26.11 kilotons. Therefore, owing to the occurrence of this supply chain, the NO_x emissions increased by 20.37 kilotons.

Table 2. Balance of the avoided emissions of the electricity and heat supply chain network between BTH cities and other provinces (unit: kiloton)

Supply chain		Emissions from nonlocal production	Emissions from local production	Balance of the avoided emissions
From	To			
Tangshan	Jiangsu	26.11	5.74	20.37

(electricity and heat)	(equipment manufacturing)			
Shijiazhuang (electricity and heat)	Jiangsu (equipment manufacturing)	20.02	2.21	17.81
Handan (electricity and heat)	Jiangsu (equipment manufacturing)	17.06	3.75	13.31
Tianjin (electricity and heat)	Jiangsu (equipment manufacturing)	15.24	5.27	9.97
Tangshan (electricity and heat)	Guangdong (equipment manufacturing)	14.20	3.33	10.88
Inner Mongolia (electricity and heat)	Beijing (construction	13.99	2.60	11.38
Zhangjiakou (electricity and heat)	Jiangsu (equipment manufacturing)	13.72	1.22	12.50
Shanxi (electricity and heat)	Beijing (construction)	11.46	2.14	9.32
Tangshan (electricity and heat)	Zhejiang (equipment manufacturing)	11.27	2.37	8.89
Tianjin (electricity and heat)	Guangdong (equipment manufacturing)	10.80	4.15	6.65
Shijiazhuang (electricity and heat)	Guangdong (equipment manufacturing)	10.52	1.24	9.28

The transfer pattern of the embodied NO_x flows originating from the metal sector (Figure 2b) is similar to that of the embodied NO_x flows originating from the electricity and heat sector. However, the flows from the metal sector to BTH mostly terminate in two sectors, namely, the construction sector (27%) and the equipment manufacturing sector (27%). The main metal consumer in BTH is the construction sector in Beijing, Baoding and Shijiazhuang and the equipment manufacturing sector in Beijing, Baoding and Cangzhou. Particularly, in the metal supply chain network, Tangshan plays a more prominent role in the production sector of the metal industry in BTH, accounting for 34% of the total NO_x emissions stemming from the metal sector in BTH. Moreover, the emission intensity of Tangshan is slightly lower than that of the metal industry in the southeast coastal provinces, but the emission intensities of the northern provinces (Inner Mongolia and Henan) are much higher than that of Tangshan. Therefore, Tangshan and the eastern coastal supply chains of metal products reduce emissions. However, the supply chains of steel products originating from other northern provinces to the Beijing construction sector may yield additional emissions. Therefore, the construction sector in BTH should adopt local steel products as much as possible and reduce the imports from other northern provinces.

Figure 2c shows that the main embodied NO_x flows originating from the nonmetal sector mainly extend to the construction sector in BTH (60%). The main nonmetal consumer in BTH is the construction sector in Beijing, Baoding, Shijiazhuang and Langfang. Thus, the embodied NO_x emissions in the supply chains are transferred from industrial cities in BTH (Tangshan, Shijiazhuang and Zhangjiakou) and northern provinces (Inner Mongolia and Henan) to the central part of BTH (Beijing, Tianjin, Baoding, Shijiazhuang and Langfang). The nonmetal supply chain network is inefficient both within the BTH region and between BTH and other provinces because of the higher emission intensities of the production-oriented cities and provinces.

3.3. Critical Supply Chain Paths

This study further extracted critical supply chain paths via SPA (see Equations 9 and 10) from the supply and demand perspectives (please refer to Tables 3 and 4). As indicated in Table 3, from the supply viewpoint, Tangshan is the key city of the intercity supply chain paths because the top ten intercity supply chain paths in BTH all flow from the electricity and heat sector to the metal smelting and pressing and metal ore mining sectors in Tangshan. As the pillar industry of Tangshan, the combined primary inputs of the metal smelting and pressing and metal ore mining sectors produce 185131 tons of NO_x emissions originating from the electricity and heat sector in other cities across BTH (occupying 10% of the BTH total emissions). The top intercity supply chain path from the supply viewpoint indicates that 54632 tons of NO_x emissions stemming from the metal smelting and pressing sector in Tangshan is directly caused by the primary inputs of the electricity and heat sector in Baoding. From the demand viewpoint, the construction sector plays an important role in the supply chain paths in BTH because most critical intercity supply chain paths terminate at the final demand of the construction sector in Baoding and Shijiazhuang. The top intercity supply chain path in BTH from the demand viewpoint reveals that 9108.95 tons of NO_x emissions stemming from the nonmetal mineral product sector in Shijiazhuang is caused by the final demand for products of the construction sector in Baoding. The second intercity supply chain path demonstrates that 8511.24 tons of NO_x emissions stemming from the nonmetal mineral product sector in Tangshan is attributed to the final demand of the construction sector in Shijiazhuang. The third intercity supply chain path indicates a similar relationship of these two sectors between Tangshan and Baoding.

The SPA results regarding the supply chain paths between BTH cities and other provinces are listed in Table 4. From the supply viewpoint, most of the critical national supply chain paths are related to the nonmetal mineral product, electricity and heat and metal smelting and pressing sectors in the northern provinces, and all flow to Beijing and Tianjin (mainly to the construction sector). The top national supply chain path from the supply viewpoint indicates that 19793 tons of NO_x emissions stemming from the construction sector in Beijing is directly caused by the primary inputs of the nonmetal mineral product sector in Henan province. The second supply chain path reveals a similar relationship of these two sectors between Tianjin and Henan. From the demand viewpoint, most of the critical national supply chain paths terminate at the final demand of the electrical equipment and common and special equipment sectors in the southeastern coastal provinces from the metal smelting and pressing sector in Handan and Tangshan. The top national supply chain path from the demand viewpoint reveals that 1944 tons of NO_x emissions originating from the metal smelting and pressing sector in Handan is attributed to the final demand for products of the electrical equipment sector in Jiangsu province. The second national supply chain path demonstrates that 1377 tons of NO_x emissions stemming from the metal smelting and pressing sector in Handan is also caused by the final demand for products of the common and special equipment sector in Jiangsu province.

Table 3. Top ten intercity supply chain paths inducing NO_x emissions in BTH from the supply and demand viewpoints

Rank	Intercity supply chain paths (supply viewpoint)	NO_x emissions (tons)	Intercity supply chain paths (demand viewpoint)	NO_x emissions (tons)
1	BD: Electricity and heat→TS: Metal smelting and pressing	27316.14	SJZ: Nonmetal mineral product and pressing→BD: Construction	9108.95
2	SJZ: Electricity and heat→TS: Metal smelting and pressing	26022.47	TS: Nonmetal mineral product→SJZ: Construction	8511.24
3	ZJK: Electricity and heat→TS: Metal smelting and pressing	22037.65	TS: Nonmetal mineral product→BD: Construction	8491.98
4	HD: Electricity and heat→TS: Metal smelting and pressing	19513.01	BD: Electricity and heat→TS: Metal smelting and pressing	8305.38
5	BD: Electricity and heat→TS: Metal ore mining	17995.55	TS: Metal smelting and pressing→BD: Construction	7973.61
6	SJZ: Electricity and heat→TS: Metal ore mining	17143.29	XT: Nonmetal mineral product and pressing→ BD: Construction	7680.04
7	QHD: Electricity and heat→TS: Metal smelting and pressing	15363.84	XT: Nonmetal mineral product and pressing→ SJZ: Construction	7642.29
8	ZJK: Electricity and heat→TS: Metal ore mining	14518.14	ZJK: Electricity and heat→TS: Metal smelting and pressing	7345.88
9	HD: Electricity and heat→TS: Metal ore mining	12854.93	SJZ: Electricity and heat→HD: Metal smelting and pressing	7074.16
10	CZ: Electricity and heat→TS: Metal ore mining	12366.59	HD: Electricity and heat→TS: Metal smelting and pressing	6504.34

Please refer to Table S1 for abbreviations.

Table 4. Top ten national supply chain paths inducing NO_x emissions from the supply and demand viewpoints

Rank	National supply chain paths (supply viewpoint)	NO_x emissions (tons)	National supply chain paths (demand viewpoint)	NO_x emissions (tons)
1	HEN: Nonmetal mineral product and pressing→BJ: Construction	19793.96	HD: Metal smelting and pressing→JS: Electrical equipment	1944.81
2	HEN: Nonmetal mineral product and pressing→TJ: Construction	16943.01	TS: Metal smelting and pressing→JS: Common and special equipment	1377.21
3	LN: Nonmetal mineral product and pressing→BJ: Construction	12341.03	TS: Metal smelting and pressing→ZJ: Common and special equipment	1083.23
4	SX: Electricity and heat→BJ: Electricity and heat	11759.60	HD: Metal smelting and pressing→JS: Common and special equipment	979.36
5	LN: Nonmetal mineral product and pressing→TJ: Construction	10865.65	TS: Metal smelting and pressing→GD: Electrical equipment	870.94
6	NMG: Nonmetal mineral product and pressing→BJ: Construction	9512.94	TS: Nonmetal mineral product and pressing→ JS: Construction	790.03
7	NMG: Electricity and heat→BJ: Electricity and heat	8118.58	HD: Metal smelting and pressing→ZJ: Common and special equipment	770.31
8	NMG: Nonmetal mineral product and pressing→TJ: Construction	7235.92	HD: Metal smelting and pressing→GD: Electrical equipment	619.34
9	NMG: Metal smelting and pressing→BJ: Metal smelting and pressing	2572.52	HD: Metal smelting and pressing→GD: Metal product	527.48
10	NMG: Metal smelting and pressing→BJ: Metal product	2361.85	NMG: Nonmetal mineral product and pressing→BJ: Construction	458.78

Only the supply chain paths involving BTH cities are noted (please refer to Table S1 for abbreviations).

4. Conclusion

The city-level results reported in this study identify hotspots of supply chains related to BTH urban agglomeration implications. Compared with other previous similar studies (Yang et al., 2018), the NO_x transfer network among cities in Hebei province is analyzed and the role of cities is repositioned. Based on the emission characteristics of the various cities, Tangshan exhibits the highest production-based NO_x emissions, and Beijing attains the highest consumption-based emissions in BTH. Hebei province, as a whole, is a production-oriented province. However, Baoding, Langfang and Cangzhou are consumption-oriented cities in Hebei province. The electricity and heat, metal, and nonmetal sectors in the industrial cities across the BTH and other production-oriented provinces are the main suppliers in the NO_x supply chains.

As for the urban supply chain of BTH, there have been researches on the urban carbon chain and water chain of Beijing-Tianjin-Hebei (Zheng et al., 2019b). They found carbon and water supply chains in BTH are both inefficient. However, we found that not all of the supply chains in BTH are inefficient for air pollutant emissions. For example, in the aspect of the electricity and heat sector, the intercity supply chain networks related to NO_x are effective within the BTH region, which transfer electricity and heat from low-emission intensity cities to high-emission intensity cities, while the supply chain network between BTH cities and other provinces exhibits the opposite result. In terms of the metal sector, the emission intensity of Tangshan is slightly lower than that of the metal industry in the southeast coastal provinces, and the supply chain is efficient. Only the Inner Mongolia metal sector and the Beijing construction sector exhibit significant inefficient supply chain relationships. However, in regard to the nonmetal supply chain network, inefficient supply chains commonly occur among cities within the BTH region and between BTH and northern provinces.

According to the obtained SPA results, in the BTH region, the critical intercity supply chain paths mainly terminate at the final demand of the construction sector, and the metal sector in Tangshan is an important supply chain node. Therefore, upstream construction enterprises can conduct green procurement for downstream metal and non-metal enterprises, thus encouraging production enterprises to control the emission intensity of air pollutants. This also helps in the technical renovation of important production nodes, such as the metal sector in Tangshan.

Outside the BTH region, from the supply viewpoint, most of the critical supply chain paths are related to the electricity and heat, nonmetal and metals sectors in the northern provinces, and all supply chains flow to Beijing and Tianjin (mainly to the construction sector). From the demand viewpoint, most of the critical supply chain paths of BTH cities terminate at the final demand of the equipment manufacturing sector in southeast coastal provinces. From the perspective of the whole country, it is necessary to strengthen the coordination of emission reduction among different regions, and pollution control costs should be internalized in commodity prices. However, during the short period, the cost of reducing pollution is mainly undertaken by the source region of the supply chain because of market competition pressure. Therefore, a cross-regional compensator system or capital and technical cooperation system is a feasible method to share the cost of pollution control along the supply chain in the future.

5. Discussion

The results of this study provide a new idea to solve the air pollution problem, namely, the effective reduction in the total amount of pollutants given the existing supply chain networks. First, it is vital to take advantage of the supply chains to reduce emissions. We should employ the supply chains of regions with a low-emission intensity to supply high-emission intensity regions. For example, in BTH, electricity and heat are transferred from low-emission intensity areas to high-emission intensity areas. Moreover, the pulling effect of consumption on air pollutants should not be ignored. The government should take the lead in the implementation of green procurement programs. Financial incentives could be offered to enterprises purchasing products from low-emission intensity enterprises.

Second, many supply chains increase the total amount of NO_x emissions, mainly because the technical level of production-oriented areas lags behind that of consumption-oriented areas, leading to the same products being produced in high-emission intensity areas and consumed in low-emission intensity areas, yielding additional NO_x emissions. If polluting enterprises are transferred to low-emission intensity areas, this may reduce the overall emissions of pollutants, but regions with a high technical level and low emission intensity are often well-developed regions. According to the theory of industrial structure evolution, the industrial structure of well-developed areas gradually evolves to contain the tertiary industry or high-tech industry with a high added value. Such contradictions could be addressed through technology transfer and assistance to reduce the emission intensities of production-oriented cities. Therefore, it is necessary to design a reasonable regional air quality responsibility definition method from the perspective of a joint regional prevention and control system. This could be an effective measure to establish a capital and technical cooperation system between the key node cities of supply chains, for example, a capital and technical cooperation system could be established between Tangshan and its major steel product consumption regions.

Finally, it is also worth further examining the combined effects of atmospheric transmission and supply chain transfer on air pollutants. Most production-oriented areas, such as Shijiazhuang, Tangshan, Handan in Hebei and Shanxi, and Henan provinces, respectively, are located along atmospheric transmission channels identified by the government (Ministry of Ecology and Environment, 2017). The unfavorable geography of the BTH region, which is characterized by the Yanshan Mountains to the north and the Taihang Mountains to the west, results in secondary pollutants being difficult to disperse (Qu et al., 2020). Superposition of the effects of the supply chains and atmospheric transmission may make it difficult to eliminate air pollution in the BTH region. Considering the joint impacts of economic linkage and atmospheric transmission, this kind of supply chain layout not only increases the environmental burden on production-oriented cities but also likely fails to effectively reduce the air pollutant level in consumption-oriented cities. The natural and economic coupling effects of air pollutants should be studied further. If the contribution of these effects is notable, this may encourage consumption-oriented cities to invest in production-oriented cities in the form of transfer payments.

This study selects the BTH urban agglomeration as an example to analyze pollution-related intercity supply chains from new perspectives. Certain uncertainties remain in the MRIO table due to the lack of intercity trade observation data. In addition, the compilation of city-level NO_x emission data inherently contains limitations. This article does not rely on the latest annual data. The reason is that the most recent official emission data of cities in China are not available to the public. However, this article focuses on the relative relationship between cities, which may be assumed to remain stable during periods lasting a few years. This paper quantitatively provides a research paradigm to reveal the supply chains among cities from a pollutant perspective and enhances the understanding of the impact of these supply chains on the atmospheric environment. The linkages among cities require further verification in the future when new data become available.

Supporting Information

Details on the regional abbreviations and sectors, emission data, methods, and extended model results are included (Figures S1–S2 and Tables S1–S10)

Notes

The authors declare no competing financial interests.

Acknowledgments

This work is financially supported by the National Natural Science Foundation of China (41871211, 71974141, and 71834004).

References

Bai, Y., Zheng, H., Shan, Y., Meng, J., Li, Y., 2021. The Consumption-Based Carbon Emissions in the Jing-Jin-Ji Urban Agglomeration Over China's Economic Transition. Earth's Future 9(9), e2021EF002132.

China Emission Accounts & Datasets, 2021. Multi-regional input-output table of Beijing-Tianjin-Hebei urban agglomeration in 2012. https://www.ceads.net.cn/data/input_output_tables/. (Accessed 18 March 2021).

Defourny, J., Thorbecke, E., 1984. Structural path analysis and multiplier decomposition within a social accounting matrix framework. The Economic Journal 94(373), 111-136.

Feng, T., Du, H.B., Zhang, Z.K., Mi, Z.F., Guan, D.B., Zuo, J., 2020. Carbon transfer within China: Insights from production fragmentation. Energy Economics 86, 12.

Ghosh, A., 1958. Input-output approach in an allocation system. Economica 25(97), 58-64.

He, W., Wang, Y., Zuo, J., Luo, Y., 2017. Sectoral linkage analysis of three main air pollutants in China's industry: Comparing 2010 with 2002. Journal of Environmental Management 202, 232-241.

Huo, H., Zhang, Q., Guan, D., Su, X., Zhao, H., He, K., 2014. Examining Air Pollution

in China Using Production- And Consumption-Based Emissions Accounting Approaches. Environmental Science & Technology 48(24), 14139-14147.
Jackson, R., Murray, A., 2004. Alternative input-output matrix updating formulations. Economic Systems Research 16(2), 135-148.
Lenzen, M., 1998. Primary energy and greenhouse gases embodied in Australian final consumption: an input-output analysis. Energy Policy 26(6), 495-506.
Li, X., Yang, L., Zheng, H., Shan, Y., Zhang, Z., Song, M., Cai, B., Guan, D., 2019. City-level water-energy nexus in Beijing-Tianjin-Hebei region. Applied Energy 235, 827-834.
Liu, Z., Huang, Q., He, C., Wang, C., Wang, Y., Li, K., 2021. Water-energy nexus within urban agglomeration: An assessment framework combining the multiregional input-output model, virtual water, and embodied energy. Resources, Conservation and Recycling 164, 105113.
Mi, Z., Meng, J., Guan, D., Shan, Y., Song, M., Wei, Y.-M., Liu, Z., Hubacek, K., 2017. Chinese CO2 emission flows have reversed since the global financial crisis. Nature Communications 8, 1712.
Miao, Y., Che, H., Zhang, X., Liu, S., 2020. Relationship between summertime concurring PM2.5 and O3 pollution and boundary layer height differs between Beijing and Shanghai, China. Environmental pollution (Barking, Essex : 1987), 115775-115775.
Miller, R.E., Blair, P.D., 2009. Input-output analysis: foundations and extensions. Cambridge university press.
Miller, R.E., Lahr, M.L., 2001. A taxonomy of extractions. Contributions to Economic Analysis 249, 407-441.
Ministry of Ecology and Environment of PRC, 2014. Air pollution governance plan of key industries in Beijing-Tianjin-Hebei and surrounding areas (2014). http://www.mee.gov.cn/gkml/hbb/bwj/201407/W020140729536850259419.pdf. (Accessed 18 March 2021).
Ministry of Ecology and Environment of PRC, 2017a. Air pollution prevention and control plan of Beijing-Tianjin-Hebei and surrounding regions in 2017.

http://dqhj.mee.gov.cn/dtxx/201703/t20170323_408663.shtml. (Accessed 18 March 2021).
Ministry of Ecology and Environment of PRC, 2017b. The sewage discharge coefficient and material balance method applicable to the industry under discharge permit administration are not included. http://www.mee.gov.cn/gkml/hbb/bgg/201712/W020171229531707207341.pdf. (Accessed 27 March 2021).
Ministry of Ecology and Environment of PRC, 2018. Law of the People's Republic of China on the Prevention and Control of Atmospheric Pollution. http://fgs.mee.gov.cn/fl/201811/t20181129_676290.shtml. (Accessed 27 March 2021).
Ministry of Ecology and Environment of PRC, 2019. Action Plan for comprehensive Air pollution Control in autumn and winter 2019-2020 in The Beijing-Tianjin-Hebei Region and surrounding regions. http://www.mee.gov.cn/xxgk2018/xxgk/xxgk03/201910/t20191016_737803.html. (Accessed 27 March 2021).
Ministry of Ecology and Environment of PRC, 2020. Report on the State of Environment in China 2019. http://www.luoshan.gov.cn/ueditor/php/upload/file/20200603/1591143599925042.pdf. (Accessed 18 March 2021).
National Bureau of Statistics of China, 2013. National Environmental Yearbook 2012. China Statistics Press, Beijing.
Qi, J., Wang, Y., Liang, S., Li, Y., Li, Y., Feng, C., Xu, L., Wang, S., Chen, L., Wang, D., Yang, Z., 2019. Primary Suppliers Driving Atmospheric Mercury Emissions through Global Supply Chains. One Earth 1(2), 254-266.
Qian, Y., Zheng, H., Meng, J., Shan, Y., Zhou, Y., Guan, D., 2022. Large inter-city inequality in consumption-based CO2 emissions for China's pearl river basin cities. Resources, Conservation and Recycling 176, 105923.
Qu, L., Liu, S., Ma, L., Zhang, Z., Du, J., Zhou, Y., Meng, F., 2020. Evaluating the meteorological normalized PM2.5 trend (2014-2019) in the "2+26" region of China

using an ensemble learning technique. Environmental Pollution 266, 115346.

Sillman, S., Logan, J.A., Wofsy, S.C., 1990. The sensitivity of ozone to nitrogen oxides and hydrocarbons in regional ozone episodes. Journal of Geophysical Research: Atmospheres 95(D2), 1837-1851.

The Central Committee of the Communist Party of China, 2020. The Fourteenth Five-Year Plan for National Economic and Social Development and the 2035 Vision Goals. https://baijiahao.baidu.com/s?id=1694073331045922804&wfr=spider&for=pc. (Accessed 28 March 2021).

Wang, Y., Bi, F., Zhang, Z., Zuo, J., Zillante, G., Du, H., Liu, H., Li, J., 2018. Spatial production fragmentation and PM2.5 related emissions transfer through three different trade patterns within China. Journal of Cleaner Production 195, 703-720.

Wang, Y., Li, X., Sun, Y., Zhang, L., Qiao, Z., Zhang, Z., Zheng, H., Meng, J., Lu, Y., Li, Y., 2020. Linkage analysis of economic consumption, pollutant emissions and concentrations based on a city-level multi-regional input–output (MRIO) model and atmospheric transport. Journal of Environmental Management 270, 110819.

Wang, Y., Li, Y., Qiao, Z., Lu, Y., 2019. Inter-city air pollutant transport in The Beijing-Tianjin-Hebei urban agglomeration: Comparison between the winters of 2012 and 2016. Journal of Environmental Management 250, 109520.

Wang, Y., Liu, H., Mao, G., Zuo, J., Ma, J., 2017. Inter-regional and sectoral linkage analysis of air pollution in Beijing-Tianjin-Hebei (Jing-Jin-Ji) urban agglomeration of China. Journal of Cleaner Production 165, 1436-1444.

Wen, L., 2015. The Beijing-Tianjin-Hebei region will invest 5.9 billion yuan to control air pollution. https://finance.huanqiu.com/article/9CaKrnJM6JK. (Accessed March 27 2021).

Yang, X., Zhang, W., Fan, J., Yu, J., Zhao, H., 2018. Transfers of embodied PM2.5 emissions from and to the North China region based on a multiregional input-output model. Environmental Pollution 235, 381-393.

Zhang, X., Zhao, T., Wang, J., Wei, Y., 2021. The embodied CO2 transfer across sectors of cities in Jing-Jin-Ji region: combining multi-regional input-output analysis with complex network analysis. Environmental Science and Pollution Research 28(32), 44249-44263.

Zhao, H., Zhang, Q., Huo, H., Lin, J., Liu, Z., Wang, H., Guan, D., He, K., 2016. Environment-economy tradeoff for Beijing–Tianjin–Hebei's exports. Applied Energy 184, 926-935.

Zheng, H., Meng, J., Mi, Z., Song, M., Shan, Y., Ou, J., Guan, D., 2019a. Linking city-level input-output table to urban energy footprint: Construction framework and application. Journal of Industrial Ecology 23(4), 781-795.

Zheng, H., Többen, J., Dietzenbacher, E., Moran, D., Meng, J., Wang, D., Guan, D., 2021. Entropy-based Chinese city-level MRIO table framework. Economic Systems Research, 1-26.

Zheng, H., Xu, L., 2020. Production and consumption-based primary PM2.5 emissions: Empirical analysis from China's interprovincial trade. Resources, Conservation and Recycling 155, 104661.

Zheng, H., Zhang, Z., Zhang, Z., Li, X., Shan, Y., Song, M., Mi, Z., Meng, J., Ou, J., Guan, D., 2019b. Mapping carbon and water networks in the north China urban agglomeration. One Earth 1(1), 126-137.