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The unequal exchange of air pollution and economic benefits embodied in Beijing-Tianjin-Hebei's consumption

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ABSTRACT

China's most critically air polluted area, the Beijing-Tianjin-Hebei (BTH) region has attracted significant attention; the regional linkage of environmental indicators in BTH has been widely studied in recent years. The city-level air pollutants and economic benefits hidden in trade activities are still poorly understood. This paper examines air pollutants and economic benefits embodied in BTH's consumption based on a city-level input-output table. Our results show that transfer flows of air pollutants and value-added between different cities lead to the unequal exchange of air pollution and economic benefits in BTH. Beijing gains more value-added (38.40%) through trade compared with its atmospheric pollutant equivalents (APE, 1.75%) induced by consumption demand in BTH. Conversely, Tangshan, Shijiazhuang, and Handan emit more air pollutants compared with the benefits they gain through trade. The results provide evidence for the establishment of compensation mechanisms between cities.

1. Introduction

The Beijing-Tianjin-Hebei (BTH) region is located in North China and includes Beijing, Tianjin, and eleven cities in the Hebei province. The Political Bureau of the Central Committee of the Communist Party of China reviewed and approved the "Outline of Beijing-Tianjin-Hebei Cooperative Development Planning" in 2015, in which the coordinated development of BTH became one of three national strategies. As the "capital economic circle," BTH has been the most dynamic region in North China. Accounting for 2.3% of the total national area, BTH generated nearly 10% of China's GDP in 2017. Although the economy is developing rapidly, the BTH area faces serious environmental problems, particularly air pollution (Xu et al., 2021). The proportion of days with good air quality in BTH (56.0%) is the lowest among the three major urban agglomerations in China (Ministry of Ecological Environment of the People's Republic of China, 2019). According to the Report on China's Ecological Environment in 2018, half of the ten cities with the worst air quality in China were located in the BTH region.

In order to control air pollution in BTH, the government issued a series of policies such as the Air Pollution Control Program of BTH and Surrounding Areas in 2017. Most policies focus on the local government's environmental responsibility in its administrative region. However, pollutants in one region are also influenced by consumption demand from other regions (Chen and Chen, 2016; Li et al., 2016; Xu et al., 2020). Therefore, air pollutants in one region are affected by other regions through trade activities, a concept referred to as embodied air pollutants. Critically, the embodied air pollutants index describes the regional linkage of atmospheric problems through trade or the supply chain (Yang et al., 2020). As China's most seriously air polluted area, the regional linkage of embodied air pollutants in BTH has attracted considerable attention (Yang et al., 2013; Zhao et al., 2016). However, the regional linkage of embodied air pollutants between cities in BTH is still poorly understood (Zhao et al., 2017). Moreover, relevant studies mainly focus on emissions while neglecting the economic benefits hidden in trade activities. This paper analyzes both embodied air pollutants and value-added between cities in BTH based on a city-level multi-region input-output table to fill this research gap.

Embodied air pollutants refer to the air pollutants of one region being caused by the consumption demand of other regions through trade, which is widely used to describe the regional linkage of environmental problems. The input-output table presents relationships between consumption and product supply across all sectors. An environmentally-extended input-output model is a top-down analytical method used to analyze sectoral linkages of pollutants (Yang et al., 2013). The multi-region input-output table can further explore the supply relationship between sectors in different regions (Druckman and

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Jackson, 2009). Therefore, the multi-region input-output model has been widely used in the field of regional or sectoral linkage of environment problems, including carbon emissions (Lévay et al., 2021; Osei-Owusu Kwame et al., 2020; Zheng et al., 2017), energy (Chen et al., 2017; Dorninger et al., 2021; Zhang et al., 2016), water (Rivera-Basques et al., 2021; Wang and Chen, 2016; Yu et al., 2010), and air pollutants (Lin et al., 2014; Yang et al., 2018a; Yang et al., 2018b). This paper adopts a multi-region input-output model to estimate embodied air pollutants in BTH.

Scholars have paid considerable attention to embodied carbon emissions due to its close relationship with global climate change (Nabernegg et al., 2019; Peters and Hertwich, 2008; Skelton et al., 2011; Tunç et al., 2022). These scholars have demonstrated that there are significant emissions embodied in trade between BTH and other Chinese regions (Mi et al., 2020, 2017). Given the severity of China's air pollution problem in recent years, more attention has been paid to embodied air pollutants (Huo et al., 2014; Wang et al., 2018; Xu et al., 2020; Zhang et al., 2017). Previous studies on the BTH region have analyzed air pollutants embodied in external trades of BTH (Zhang et al., 2018; Zhao et al., 2016). Meanwhile, some studies analyze air pollutants flows within BTH, though many treat Hebei province as a whole region without accounting for differences between cities (Wang et al., 2017b; Yang et al., 2013). For instance, Yang et al. (2013) analyzed the transferring routes of total suspended particulate matter in the area, while Wang et al. (2017b) captured both inter-regional and sectoral linkage analysis of air pollution in BTH. However, previous studies regard Hebei province as a whole region without considering differences between cities.

The Hebei province in BTH includes eleven cities, and within these cities, there are significant differences in development stages, industrial structures, and pollution control technologies. Zheng et al. (2018) compile a city-level multi-region input-output table for the Hebei province in China and apply it to city-level energy footprint accounting of the North China urban agglomeration. Li et al. (2019) account for the city-level water-energy nexus in BTH in 2012 from production and consumption perspectives. In terms of city-level air pollution in BTH, Wang et al. (2019) study the cross-boundary transmission of air pollutants between cities in BTH. However, consumption demand between regions through supply chains not only causes air pollutants but also creates value-added (Zhao et al., 2016). Prell (2016) analyzes the wealth and pollution inequalities of global trade based on a network and input-output approach. Prell et al. (2014) compare the economic gains and environmental losses of US consumption and find that the US gains a larger share of value-added than its share of pollution through global trade. Yu et al. (2014) examine environmental indicators and value-added embodied in China's trade activities with the rest of the world and find that trade leads to the mismatch between regional environmental burden and economic benefits. For the BTH region in China, Zhao et al. (2016) quantify embodied air pollutants and economic gains in BTH's exports on a sectoral basis. They find that exports lead to a higher ratio of air pollutants than economic gains in BTH. However, the trade-off between air pollution and economic benefits of different cities within BTH is absent to date. In this paper, we focus on city-level air pollutants and the value-added embodied in internal trades of BTH to fill the research gap. We consider BTH as a closed-loop economy, and ignore air pollutants embodied in exports, imports, and trade between BTH and other Chinese regions. We investigate the transfer of embodied air pollutants and value-added between cities in BTH based on a city-level multi-region input-output table. We further analyze city-level unequal exchange of air pollution and economic benefits in BTH.

The remainder of this paper is structured as follows. Section 2 introduces the methodology and data sources of the paper. Section 3 presents the results of air pollutants and value-added embodied in BTH's consumption, and discusses the unequal exchange of air pollution and economic benefits in the area. Conclusions are presented in Section 4.

2. Methodology and data

2.1. Multi-region input-output model

The input-output tables incorporate both competitive and non-competitive input-output tables (Chen et al., 2017; Su and Ang, 2013). Compared to a non-competitive input-output table, the competitive input-output table fails to distinguish between domestic and imported commodities. Therefore, this paper adopts a non-competitive multi-region input-output table to measure air pollutants and value-added embodied in BTH's consumption. The basic structure of the non-competitive input-output table is shown in Table 1.

(Notes: $\mathbf{Z}$ is the intermediate input matrix. $\mathbf{f}$ is the final consumption vector, including consumption and investment. $\mathbf{v}$ represents the value-added vector. $\mathbf{o}$ and $\mathbf{m}$ are the exports vector and imports vector respectively. $\mathbf{x}$ is the total output vector and $\mathbf{x}'$ is the total input vector.)

The following balance exists in the input-output table, covering the entire economic system:

$$\mathbf{x} = \mathbf{A}\mathbf{x} + \mathbf{y} \tag{1}$$

Where $\mathbf{x}$ is the total output vector, $\mathbf{A}$ is the direct input coefficient matrix and $\mathbf{y}$ represents the final demand vector that includes final consumption and exports. The element a_{ij}^{rs} in matrix $\mathbf{A}$ is obtained by $a_{ij}^{rs} = z_{ij}^{rs}/x_j^s$, where z_{ij}^{rs} is the input of sector i in region r that is consumed by sector j in region s and x_j^s refers to the total output of sector j in region s. According to Eq. (1), we can get:

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} \tag{2}$$

Where $\mathbf{B} = (\mathbf{I} - \mathbf{A})^{-1}$ is the Leontief inverse matrix that depicts the total production of each sector to meet the final demand of other sectors (Yang et al., 2013).

The final demand includes consumption, investment and exports. In this paper, we focus on city-level air pollutants and value-added embodied in internal trades of BTH. Therefore, we consider BTH as a closed-loop economy and ignore air pollutants embodied in exports, imports, and trade between BTH and other Chinese regions. The embodied air pollutants and value-added embodied in BTH's consumption can be obtained by introducing the air pollutants coefficient and value-added coefficient:

$$\mathbf{e} = \mathbf{QBt} \tag{3}$$

$$\mathbf{v} = \mathbf{WBt} \tag{4}$$

where $\mathbf{e}$ ($\mathbf{v}$) is the embodied air pollutants (value-added) vector of BTH, $\mathbf{Q} = \widehat{\mathbf{q}}$ ($\mathbf{W} = \widehat{\mathbf{w}}$) is the diagonal matrix of air pollutants coefficient (value-added coefficient). The element q_i^r (w_i^r) in vector $\mathbf{q}$ ($\mathbf{w}$) is given by $q_i^r = h_i^r/x_i^r$ ($w_i^r = t_i^r/x_i^r$), where h_i^r (t_i^r) represents the direct air pollutants (value-added) of sector i in region r and x_i^r is the total output of sector i in region r. $\mathbf{t}$ is the consumption vector of BTH, which ignores exports, imports, and trade between BTH and other Chinese regions. The element $e_{i,j}^{r,s}$ ($v_{i,j}^{r,s}$) in vector $\mathbf{e}$ ($\mathbf{v}$) refers to embodied air pollutants

Table 1
The basic structure of a non-competitive input-output table.

		Output			
Input		Intermediate demand	Final demand		Total output
		Region (1 … m)	Final consumption	Exports	
Intermediate input	Region (1 … m)	**Z**	**f**	**o**	**x**
Added value		**v**			
Imports		**m**			
Total input		$\mathbf{x}'$			

(value-added) emitted (gained) by sector *i* in region *r* to support consumption demand of sector *j* in region *s* (i.e., embodied air pollutants or value-added that transfer from sector *i* in region *r* to sector *j* in region *s*). The net air pollutants and value-added between sector *i* in region *r* and sector *j* in region *s* can be obtained by:

$$p_{i,j}^{r,s} = e_{i,j}^{r,s} - e_{j,i}^{s,r} \tag{5}$$

$$u_{i,j}^{r,s} = v_{i,j}^{r,s} - v_{j,i}^{s,r} \tag{6}$$

Where $p_{i,j}^{r,s} > 0$ ($u_{i,j}^{r,s} > 0$) represents that sector *i* in region *r* is a net *exporter* of air pollutants (value-added) to sector *j* in region *s*, and $p_{i,j}^{r,s} < 0$ ($u_{i,j}^{r,s} < 0$) represents that sector *i* in region *r* is a net *importer* of air pollutants (value-added) from sector *j* in region *s*. Then, net air pollutants (value-added) of sector *i* in region *r* is given by $p_i^r = \sum_{j=1}^{n}\sum_{s=1}^{m} p_{i,j}^{r,s}$ ($u_i^r = \sum_{j=1}^{n}\sum_{s=1}^{m} u_{i,j}^{r,s}$), where *n* is the total number of sectors and *m* is the total number of regions. The net air pollutants (value-added) of region *r* can be given by $p^r = \sum_{i=1}^{n} p_i^r$ ($u^r = \sum_{i=1}^{n} u_i^r$), where *n* is the total number of sectors. Net exporters of air pollutants emit extra air pollutants to support the consumption demand of other regions, and net exporters of value-added pay for their consumption. In contrast, net importers of air pollutants cause air pollutants in other regions to satisfy their own consumption demand, and net importers of value-added gain economic benefits from other regions.

The ratios of embodied air pollutants and value-added have been used to measure environment and economy trade-offs for China's exports (Zhang et al., 2018; Zhao et al., 2016). Zhang et al. (2018) build a regional economic and environmental justice index based on the disproportion of embodied air pollution and value-added. Zhao et al. (2016) analyze the environment and economy trade-off for BTH's exports based on the pollutant emission ratio and economic gains ratio. In this paper, we measure the unequal exchange of air pollution and economic benefits within BTH by comparing the ratio of APE and value-added embodied in BTH's consumption. The ratio of region *r*'s APE embodied in BTH's consumption is given by $\beta_r = e_r / \sum_{r=1}^{m} e_r$, where e_r is region *r*'s APE embodied in BTH's consumption and *m* is the total number of regions. The higher the ratio of embodied APE, the greater the likelihood that the city suffers from more serious air pollution in the inter-regional trade to meet the consumption demand of BTH. The ratio of APE embodied in BTH's consumption is given by $\gamma_r = v_r / \sum_{r=1}^{m} v_r$, where v_r is region *r*'s value-added embodied in BTH's consumption and *m* is the total number of regions. The higher the ratio of embodied value-added, the greater the likelihood that the city gains more economic benefits in the inter-regional trade to meet the consumption demand of BTH. The ratio of embodied APE reflects the city's pollution burden and negative impacts induced by internal trades of BTH, while the ratio of embodied value-added reflects the city's economic benefits and positive impacts induced by the internal trades of BTH.

We further introduce the emission intensity index to discuss each region's pollution burden per-unit profit. The emission intensity in each city is given by $\delta_r = e_r / v_r$, where e_r and v_r are region *r*'s air pollutants and value-added embodied in BTH's consumption, respectively. The higher the emission intensity, the city burdens more serious air pollution for per-unit economic benefits and faces regional economic and environmental inequality.

2.2. Data

Particulate matter (PM) has been the chief pollutant contributing to air pollution in China, and SO_2, NO_X, and soot are the main precursors of PM (Wang and Hao, 2012; Wang et al., 2017a, 2017b). In this paper, we estimate embodied air pollutants in BTH by using the data of SO_2, NO_X, and soot and the city-level input-output table for 2015. The data of SO_2, NO_X, and soot in each city were derived from the China City Statistical Yearbook. Then, based on the Sectoral Air Pollutant Emission Inventory established by Zhang et al. (2018), we estimate the sector level air pollutants data. According to Zhang et al. (2018), SO_2, NO_X, and soot were combined into an index named atmospheric pollutant equivalents (APE) to synthetically measure embodied air pollutants in BTH. The conversion coefficients of SO_2, NO_X, and soot to APE are 0.95, 0.95, and 2.18, respectively. The city-level multi-region input-output table was compiled by (Zheng et al., 2021). The original input-output table includes 313 cities in China, and each city is composed of 42 sectors. In this paper, we focus on internal trade for 13 cities in BTH. Therefore, we consider BTH as a closed-loop economy and ignore trade between BTH and other Chinese regions.

3. Results and discussions

3.1. The regional linkage of air pollution and economic benefits

Fig. 1 shows each city's APE and value-added driven by consumption in BTH. A city's APE include air pollutants driven by local consumption as well as other cities' consumption. Consumption in BTH drives most APE in Shijiazhuang (140.87 kt), followed by Tianjin (133.43 kt) and Tangshan (100.69 kt). The top three cities' APE account for 51.22% of the total APE driven by consumption in BTH. As shown in Fig. 1, APE in Beijing and Tianjin are mainly driven by their local consumption. Each city's APE driven by consumption of other cities in BTH ranges from 3% to 76%. For instance, only 3.84% of APE (5.12 kt) in Tianjin are driven by consumption of other cities, while that number rises to 75.88% (76.40 kt) in Tangshan, suggesting that other cities in BTH depend more on Tangshan than Tianjin. This finding is related to the developed steel industry in Tangshan: steel is a high emission industry and may be produced in Tangshan to provide materials for other cities, thus causing the emission of air pollutants.

Among all cities, Beijing gains the most value-added (1630.39 billion yuan) from consumption in BTH, followed by Tianjin (919.84 billion yuan). The value-added in Beijing accounts for 38.40% of total value-added gained from consumption in BTH as a whole, while APE in Beijing accounts for only 1.75% of total APE induced by consumption in BTH. This could be explained from two aspects. On the one hand, Beijing trades with other cities to meet its consumption demand and thus reduce its local pollutant emissions. On the other hand, as the economically and technologically advanced capital city, the additional value of products in Beijing is higher and could obtain higher profits. Unlike Beijing, both APE and value-added of Tianjin induced by consumption in BTH are relatively high. Tianjin is dominated by the secondary industry with high emission coefficient, which may cause significant air pollutants. Meanwhile, as one of four municipalities directly under the central government, the developed economy and technology bring more value-added and higher benefits for products in Tianjin. The APE of Shijiazhuang and Tangshan account for 33.00% of total air pollutants induced by consumption in BTH while the proportion of their value-added is only 13.80%. This is because Shijiazhuang and Tangshan are dominated by pollution-intensive heavy industries and emit more air pollutants than other cities. Compared with Beijing and Tianjin, Shijiazhuang and Tangshan are less developed regions whose additional value of products are lower and gain less value-added. Value-added in most cities is predominantly driven by their local consumption, though a city also gains value-added from other cities' consumption. Fig. 2 further shows net flows of APE and value-added between cities in BTH.

Consumption in Baoding drives most of APE (65.23 kt) in BTH, followed by Beijing (32.43 kt) and Langfang (29.00 kt). The APE driven by consumption in Beijing account for 18.31% of total importation of APE in BTH. Beijing mainly imports APE from Tangshan, Shijiazhuang, and Handan, accounting for 20.40%, 18.21%, and 12.32% of its total APE importation respectively. Consumption in Baoding and Langfang mainly drive APE in Tangshan and Shijiazhuang. Among all cities, Tangshan is the largest exporter of APE (40.89 kt), followed by Shijiazhuang (34.97 kt) and Handan (22.56 kt). These cities mainly emit air pollutants to support consumption demand in Beijing, Tianjin, and Baoding. Because

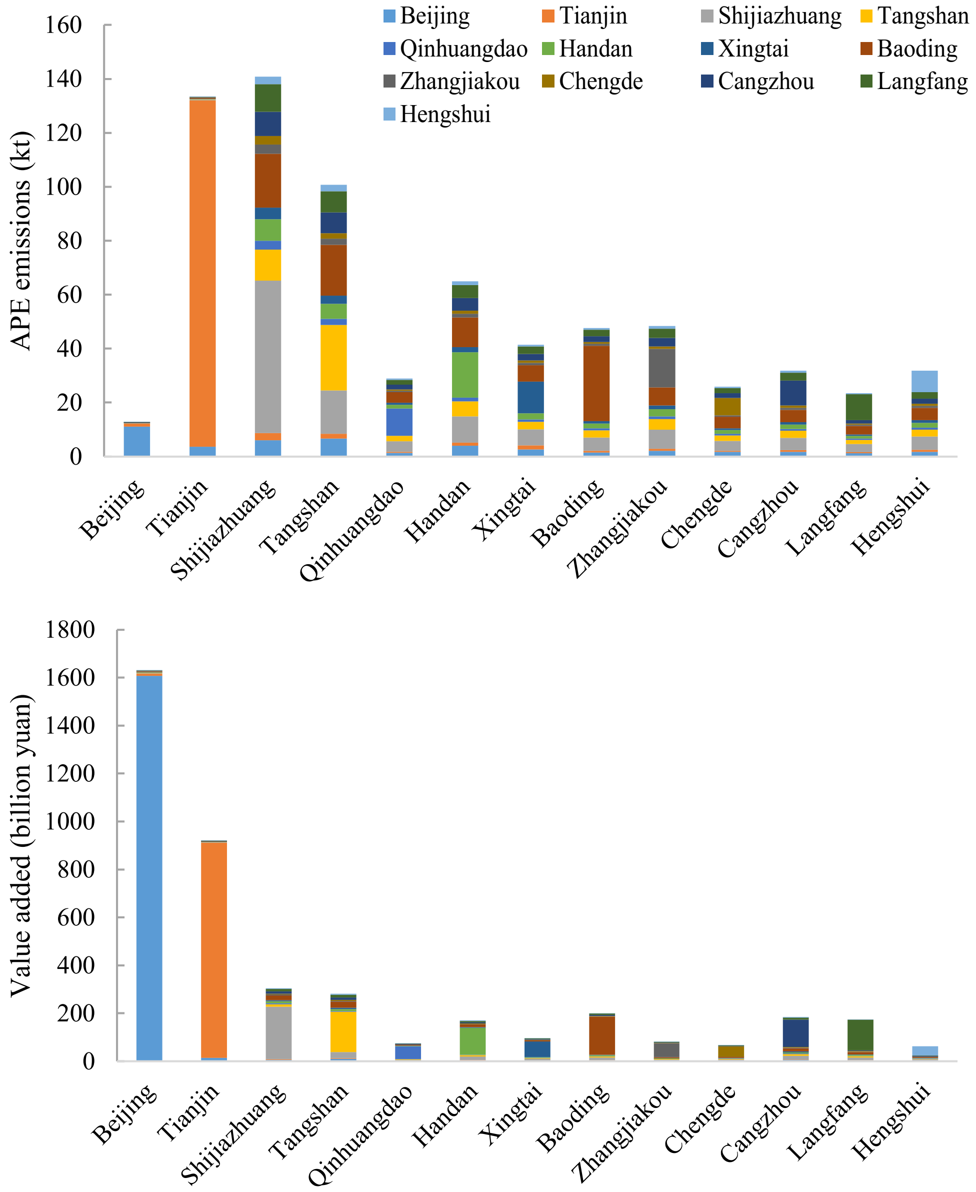

Fig. 1. Each city's APE and value-added driven by consumption in BTH.

Tangshan, Shijiazhuang and Handan are in the upstream of the supply chain, which is dominated by high pollution industries such as steel and pharmaceutical sectors, they emit air pollutants to produce commodities for regions in the downstream of the supply chain like Beijing, Tianjin, and Baoding. Significantly, 71.11% of APE exportation in Tianjin is induced by consumption in Beijing, suggesting that Tianjin mainly emits extra air pollutants to meet the consumption demand in Beijing: Tianjin is adjacent to Beijing and transportation between them is very convenient. Therefore, Beijing is more dependent on Tianjin, causing a large quantity of APE in Tianjin.

Although Tianjin emits extra air pollutants to meet the consumption demand in Beijing, it also gains value-added from Beijing. As shown in Fig. 2, Beijing accounts for 73.38% of Tianjin's total value-added importation. Tangshan is the largest importer of value-added since it emits the most air pollutants to support the consumption demand of other cities in BTH. Beijing and Baoding are main exporters of value-added because they need to pay for their consumption, which drives extra APE in other cities. The value-added exportation in Beijing and Baoding accounts for 55.55% of the total value for all cities. Beijing mainly exports value-added to Tianjin and Tangshan, while Baoding exports value-added to nearly all other cities in BTH, implying that the economic benefits of other cities depend on Baoding to a certain extent. This is because Baoding is located in the central part of BTH. Regional air pollutants and economic benefits are largely affected by the characteristics of regional industry. We further discuss the sectoral linkage of air pollution and economic benefits in BTH in the next section.

3.2. The sectoral linkage of air pollution and economic benefits

We merge the 42 sectors into 7 sectors according to their contributions to our analysis, which include the primary industry, five secondary industry sectors, and the tertiary industry. The energy and basic industry sectors are the main contributors of air pollutants emissions. The construction sector and the tertiary industry induce pollutant emissions of other sectors. The classification helps us better identify characteristics of different sectors, shown in Table 2.

Fig. 3 shows each sector's APE and value-added driven by consumption in BTH. Consumption in BTH drives most APE of the energy

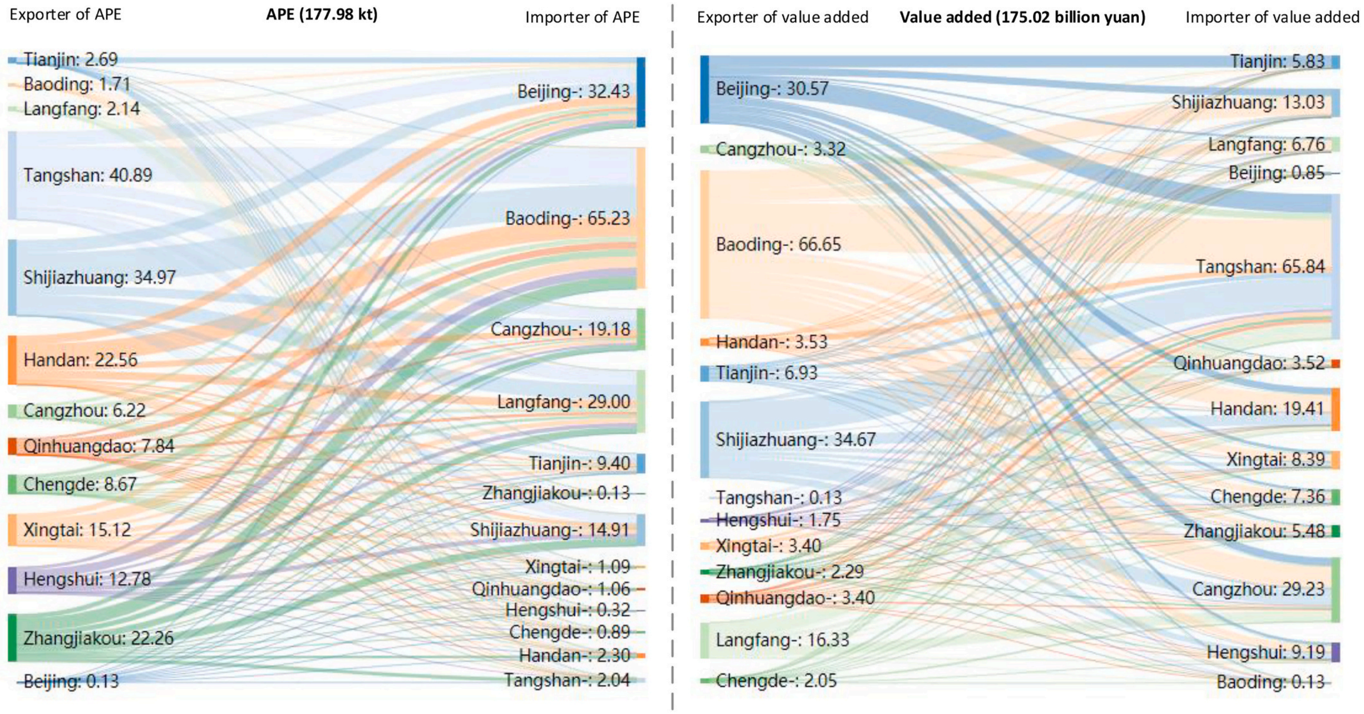

Fig. 2. Net flows of APE and value-added between cities in BTH.

industry (415.98 kt), followed by the basic industry (170.60 kt). The top two sectors' APE account for 95.97% of the total APE driven by consumption in BTH. A sector's APE include those driven by its own demand as well as other sectors' demand. As shown in Fig. 3, 352.22 kt (84.67%) of APE in the energy industry and 162.61 kt (95.32%) in the basic industry are induced by other sectors' demand. In addition to their own demand, these industries' APE is mainly induced by demand from the construction sector, the service industry, and the equipment manufacturing sector. The energy industry and the basic industry are upstream of the industry supply chain and produce raw materials for sectors downstream of the industry chain. Therefore, other sectors are highly dependent on the energy and basic industries and drive massive APE emissions of these two sectors.

Among all sectors, the service industry gains the most value-added (2374.03 billion yuan) from consumption in BTH, followed by the Construction (585.48 billion yuan). The value-added of the service industry accounts for 60.57% of total value-added gained from consumption in BTH. The service industry belongs to the high-profit tertiary industry and thus gains more value-added than other sectors. Conversely, the energy industry emits the largest quantity of air pollutants among all sectors while gaining the least value-added, accounting for 68.06% and 3.23% of total APE and value-added driven by consumption in Beijing respectively. This is because the energy industry is a pollution-intensive sector and in the upstream of the industry chain, meaning it produces commodities for other sectors and thus emits a large quantity of air pollutants. In addition, the energy industry belongs to the low-profit secondary industry and so gains less added value than other sectors. Except for its own demand, a sector also gains value-added from other sectors' consumption. Fig. 4 further shows net flows of APE and value-added between sectors in BTH.

Consumption of the construction sector drives the majority APE emissions (318.30 kt) in BTH, followed by the service industry (95.30 kt) and the Equipment Manufacturing Industry (71.70 kt). The APE driven by consumption of the construction sector account for 60.75% of the total importation of APE in BTH. The construction sector mainly imports APE from the energy industry and the basic industry, accounting for 59.89% and 38.92% of its total APE importation respectively. Consumption of the service industry mainly drives APE of the energy industry, while consumption of the Equipment Manufacturing Industry drives massive APE of the basic industry as well as the energy industry. Among all sectors, the energy industry is the largest exporter of APE (351.62 kt), followed by the basic industry (161.88 kt). They mainly emit air pollutants to support the consumption demand of the construction sector and the service industry. The energy industry provides power for other sectors and the basic industry mainly produces raw materials for other sectors. Therefore, other sectors' development strongly depends on the energy industry and the basic industry, thus they emit significant quantities of air pollutants to meet other sectors' demand.

As the basic industry emits a large amount of air pollutants to meet the consumption demand of other sectors, it gains the most value-added from other sectors. As shown in Fig. 4, the basic industry imports most value-added from the construction sector, accounting for 78.21% of its total imported value-added. Except for the basic industry, the service industry gains the most value-added from other sectors due to its high-profit characteristics. Although the energy industry emits the most APE to meet the consumption demand of other sectors, it gains less value-added from other sectors since the energy industry belongs to the pollution-intensive but low-profit secondary industry. Therefore, the regions dominated by the energy industry may face serious issues, including pollution and economic backwardness. The construction sector and the Equipment Manufacturing Industry are the top two exporters of value-added because they drive a large quantity of extra APE in other sectors. The value-added exportation of the construction sector and the Equipment Manufacturing Industry accounts for 88.43% of total value-added exportation in all cities, and they mainly export value-added to the basic industry and the service industry. The industrial characteristics of different cities in BTH vary greatly, which may cause some regions to emit significant quantities of air pollutants to meet the consumption demand of BTH while gaining relatively low value-added. We further analyze the unequal exchange of air pollution and economic benefits in BTH in the next section.

Table 2
Classification of sectors.

Sector	Original Sector
Agriculture, Forestry, Husbandry and Fishery	Agriculture, Forestry, Animal Husbandry and Fishery
Energy industry	Mining and washing of coal
	Extraction of petroleum and natural gas
	Processing of petroleum, coking, processing of nuclear fuel
	Production and distribution of electric power and heat power
	Production and distribution of gas
	Production and distribution of tap water
Basic Industry	Mining and processing of metal ores
	Mining and processing of nonmetal and other ores
	Manufacture of chemical products
	Manufacture of non-metallic mineral products
	Smelting and processing of metals
	Manufacture of metal products
Light Industry	Food and tobacco processing
	Textile industry
	Manufacture of leather, fur, feather and related products
	Processing of timber and furniture
	Manufacture of paper, printing and articles for culture, education and sport activity
Equipment Manufacturing Industry	Manufacture of general purpose machinery
	Manufacture of special purpose machinery
	Manufacture of transport equipment
	Manufacture of electrical machinery and equipment
	Manufacture of communication equipment, computers and other electronic equipment
	Manufacture of measuring instruments
	Other manufacturing
	Comprehensive use of waste resources
	Repair of metal products, machinery and equipment
Construction	Construction
Service industry	Transport, storage, and postal services
	Wholesale and retail trades
	Accommodation and catering
	Information transfer, software and information technology services
	Finance
	Real estate
	Leasing and commercial services
	Scientific research and polytechnic services
	Administration of water, environment, and public facilities
	Resident, repair and other services
	Education
	Health care and social work
	Culture, sports, and entertainment
	Public administration, social insurance, and social organizations

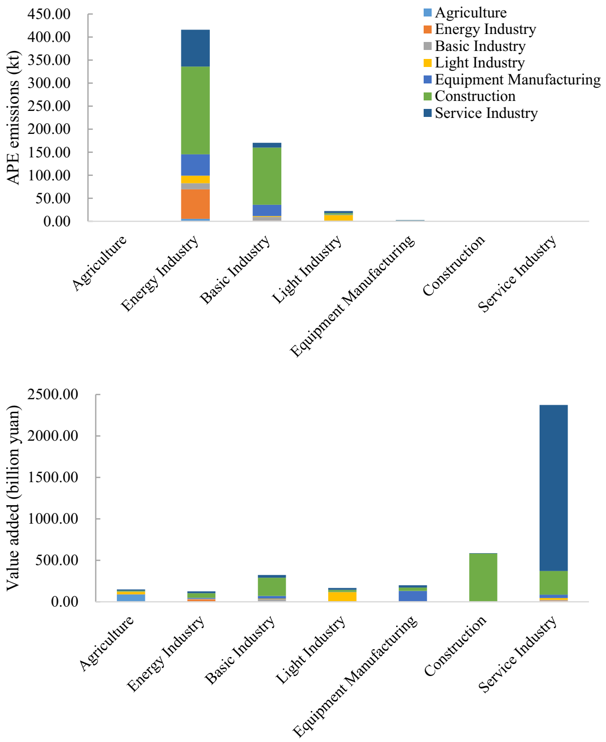

Fig. 3. Each sector's APE and value-added driven by consumption in BTH.

3.3. The unequal exchange of air pollution and economic benefits

This section measures the trade-off between air pollution and economic benefits in BTH. Table 3 shows each city's air pollutants and value-added embodied in BTH's consumption. The APE in Table 3 represents air pollutants discharged by each city in order to support the consumption demand of BTH. The value-added represents each city's economic benefits in order to support the consumption demand of BTH. Fig. 5 further depicts the distribution of the ratios of embodied APE and embodied value-added for each city. In Fig. 5, the x-axis shows the embodied APE ratio, while the y-axis shows the embodied value-added ratio for each city. We can observe each city's pollution burden as well as their economic benefits in the inter-regional trade to meet the consumption demand of BTH. We map the 13 cities in BTH in two groups by a mean line, representing the embodied APE ratio equal to the embodied value-added ratio. The cities falling below the mean line suffer from a higher proportion of air pollutants among all regions than their proportion of economic benefits, indicating inequity between the pollution and economic benefits induced by BTH's consumption. Conversely, the cities falling above the mean line gain a higher proportion of economic benefits among all regions compared with their proportion of embodied air pollutants. This is related to the industrial characteristics of different cities. Cities like Tangshan and Handan are in the upstream of the industrial chain and are dominated by pollution-intensive industries with low value-added. Beijing and Tianjin are in the downstream of the industrial chain and are dominated by high value-added industries with low emissions. Therefore, the internal trades of BTH lead to the unequal exchange of air pollution and economic benefits.

As shown in Table 3, Beijing emits 12.80 kt of APE and obtain 1630.39 billion yuan of value-added through trade activities in BTH, accounting for 1.75% and 38.40% of total embodied air pollutants and value-added, respectively (see Fig. 5). Therefore, Therefore, Beijing gains more value-added through trade than its APE emissions induced by consumption demand in BTH, so Beijing is above the mean line in Fig. 5. Conversely, Tangshan, Shijiazhuang, Handan, and Xingtai are located below the mean line in Fig. 5, indicating that they emit more air pollutants than the benefits they gain through trade and thus face an inequality of air pollution and economic benefits. For instance, Tangshan emits 100.69 kt of APE and obtains 281.30 billion yuan of value-added, accounting for 13.75% of the total embodied air pollutants and 6.62% of total embodied value-added, respectively. Some cities are near the mean line, including Qinhuangdao, Baoding, Chengde, Cangzhou, Langfang, and Hengshui. Their proximity to the mean line indicates a balance between air pollution and economic benefits, since the proportions of air pollutants they emit and the value-added they gain are relatively equal. The embodied APE emissions for each of these cities is less than 6% of the total embodied emissions, and the embodied value-added for each city is less than 5% of the total embodied value-added. Although Tianjin is near the mean line, it emits a large quantity of air pollutants to support the consumption demand of other cities and simultaneously gains considerable value-added. Tianjin emits 133.43 kt of APE to support the consumption demand in BTH and gains 919.84

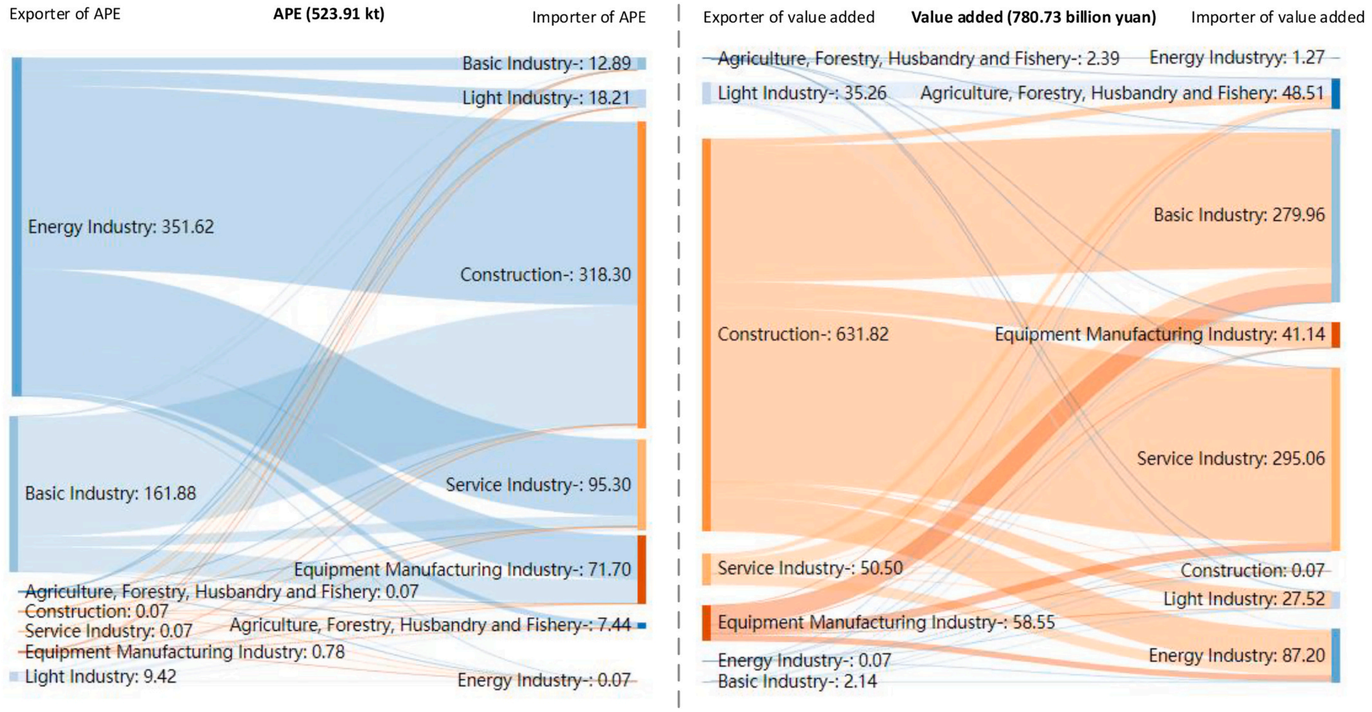

Fig. 4. Net flows of APE and value-added between sectors in BTH.

Table 3
APE and value-added embodied in BTH's consumption.

City	APE (kt)	Value-added (billion yuan)
Beijing	12.80	1630.39
Tianjin	133.43	919.84
Shijiazhuang	140.87	304.81
Tangshan	100.69	281.30
Qinhuangdao	28.96	74.11
Handan	64.93	169.95
Xingtai	41.46	95.58
Baoding	47.68	199.69
Zhangjiakou	48.32	81.18
Chengde	25.85	67.55
Cangzhou	31.85	184.11
Langfang	23.47	175.12
Hengshui	31.76	62.52

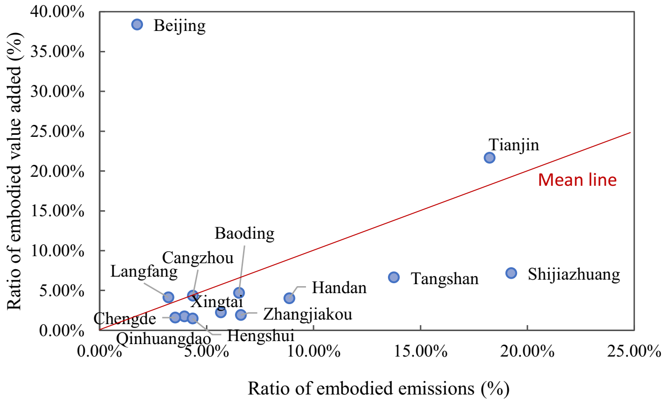

Fig. 5. Embodied air pollutants and embodied value-added of each city in BTH.

billion yuan of value-added, accounting for 18.23% of the total embodied air pollutants and 21.66% of the total embodied value-added, respectively. Therefore, the cities' roles in air pollution and economic benefits in BTH are highly variable.

Fig. 5 shows that Beijing and Tianjin gain a higher proportion of economic benefits compared with their proportion of embodied air pollutants. Tangshan and Handan suffer from a higher proportion of air pollutants compared to their proportion of economic benefits; in other words, these cities face an inequality of air pollution and economic benefits induced by BTH's consumption. We introduce the emission intensity index to explain the differences. According to the emission intensity that reflects each region's pollution burden per unit profit, the emission intensities of Beijing and Tianjin are 0.01 kt/billion yuan and 0.15 kt/billion yuan. In comparison, the emission intensities of Tangshan and Handan are 0.36 kt/billion yuan and 0.38 kt/billion yuan. Therefore, Tangshan and Handan face a more significant pollution burden than Beijing and Tianjin. Cities with advanced production technologies such as Beijing and Tianjin should transfer their techniques to cities with high emission intensities and thus decrease air pollutants emitted by other cities.

This paper analyses the city-level unequal exchange of air pollution and economic benefits embodied in BTH's consumption. The results provide rationale and evidence for the establishment of compensation mechanisms between cities. Current air quality compensation mechanisms in China are limited to cities within each province (Cui et al., 2021). According to the results of this paper, there is an unequal exchange of air pollution and economic benefits between cities across provinces. Therefore, an inter-provincial compensation mechanism is needed to balance the regional inequality of air pollution and economic benefits. Moreover, according to the current air quality compensation mechanism in the Hebei province, Tangshan and Handan should compensate for other cities since their poor pollution control. The massive air pollutants in Tangshan and Handan are driven by the consumption demand of other regions. A compensation mechanism is needed in the future from the consumption perspective to improve the current compensation mechanism. However, this paper focuses on quantifying regional inequality between cities, which is the rationale for constructing a compensation mechanism. The specific compensation process is not within the scope of this article. In future research, the details about the compensation process can be further investigated in combination with the regional abatement cost differences.

Based on the findings, we provide policy suggestions for pollution reduction from a city perspective. On the one hand, cities with high emission intensities should introduce advanced technology and equipment from surrounding cities to produce less pollution since emission intensities of cities vary considerably even for adjacent regions. Introducing equipment from surrounding cities simultaneously helps save the transport cost and lighten the unequal exchange between cities. On the other hand, cities specializing in heavy industries should transition to industries with higher value-added but lower emissions. The developed city should drive the development of less developed areas to reduce the gap between cities. In addition, except for air pollution control, all the cities in China have to promote carbon emission reduction and reach the emission peak around 2030 and emission neutrality around 2060. Since the industrial sources of air pollutants and carbon emissions are similar, a collaborative reduction of air pollutants and carbon emissions may be more effective than separate control. Therefore, air pollution and carbon emissions control measures should be integrated into future emission reduction strategies.

4. Conclusions

This paper quantifies the embodied air pollutants and value-added in BTH based on a city-level input-output table where we examine the regional and sectoral linkage s of air pollution and economic benefits in BTH. We also provide insight into the balance between embodied emissions and value-added for each city. To our knowledge, this is the first study to use the city-level input-output table to estimate both embodied air pollutants and value-added in BTH. The results can provide essential insights to a regional joint prevention and control of air pollution in the seriously polluted areas in BTH.

From a regional perspective, cities in the upstream of the supply chain, such as Tangshan, Shijiazhuang, and Handan, emit a large quantity of air pollutants to support consumption demand of cities in the downstream of the supply chain, such as Beijing, Tianjin, and Baoding. Exporters of APE are usually cities dominated by high pollution industries such as steel and pharmaceutical sectors, and they emit air pollutants to produce commodities for other regions. Importers of APE are usually economically developed cities that have a greater consumption demand. Beijing and Baoding are the top two exporters of value-added because they need to pay for their consumption which drives a large quantity of extra APE in other cities. Importers of value-added are economically developed cities with higher added value, such as Beijing and Tianjin, or cities that emit a large quantity of air pollutants to support the consumption demand of other regions and thus gain more value-added.

From a sectoral perspective, sectors in the upstream of the industry chain, including the energy industry and the basic industry, emit a large quantity of air pollutants to support the consumption demand of sectors in the downstream of the industry chain, such as the construction sector and the service industry. Exporters of APE are usually produce raw materials or provide power for other sectors and thus emit massive quantities of air pollutants. Importers of APE are usually high-profit tertiary industries like the service industry. The construction sector is the largest exporter of value-added because it should pay for its consumption that drives a large quantity of extra APE in other sectors. Importers of value-added are high-profit sectors such as the service industry, or sectors that emit a large quantity of air pollutants to meet the consumption demand of other sectors and thus gain more value-added, such as the basic industry.

Transfer flows of APE and value-added between different cities lead to regional inequality of air pollution and economic benefits in BTH. Beijing gains more value-added (38.40%) through trade compared with its APE (1.75%) induced by consumption demand in BTH. Conversely, Tangshan, Shijiazhuang, and Handan emit more air pollutants than the benefits they gain through trade. Tianjin, in particular, emits significant amounts of air pollutants (18.23%) to support the consumption demand of other cities and simultaneously gains significant value-added (21.66%). The cities' roles in air pollution and economic benefits in BTH vary significantly. A compensation mechanism may be needed to balance the regional inequality of air pollution and economic benefits in BTH. The compensation fund could also be used to develop environmental protection projects and cleaner technologies.

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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