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Environment-economy tradeoff for Beijing–Tianjin–Hebei's exports

Hongyan Zhao [a], Qiang Zhang [a,*], Hong Huo [b,*], Jintai Lin [c], Zhu Liu [d], Haikun Wang [e], Dabo Guan [a,f], Kebin He [a,g]

[a] Ministry of Education Key Laboratory for Earth System Modeling, Center for Earth System Science, Tsinghua University, Beijing, China
[b] Institute of Energy, Environment and Economy, Tsinghua University, Beijing, China
[c] Laboratory for Climate and Ocean-Atmosphere Studies, Department of Atmospheric and Oceanic Sciences, School of Physics, Peking University, Beijing, China
[d] Resnick Sustainability Institute, California Institute of Technology, Pasadena, CA 91125, USA
[e] State Key Laboratory of Pollution Control and Resource Reuse, School of Environment, Nanjing University, Nanjing, China
[f] Tyndall Centre for Climate Change Research, School of International Development, University of East Anglia, Norwich NR4 7TJ, United Kingdom
[g] State Key Joint Laboratory of Environment Simulation and Pollution Control, School of Environment, Tsinghua University, Beijing, China

HIGHLIGHTS

- A three-region input–output model was built to analyze the environment-economy tradeoff for Beijing–Tianjin–Hebei's exports.
- BTH bears more pollutant emission ratio than that of economic gains from interprovincial and international exports.
- Industrial production in Beijing and Tianjin lead to more pollutant emissions than value added in Hebei.

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ABSTRACT

The trade of goods among regions or nations associated with large environmental consequences. Yet balancing economic gains and environmental consequences induced by trade is still hindered by a lack of quantification of these two factors, especially for the environmental problems those are more locally oriented, such as the atmospheric pollution. Based on an environmental input–output analysis for 2010, we contrast economic gains (value added) against atmospheric pollutant emissions (sulfur dioxide (SO_2), nitric oxide (NO_x), primary fine particulate matter ($PM_{2.5}$) and non-methane volatile organic compounds (NMVOC)) and the widely concerned CO_2 emissions associated with international and interprovincial exports from Beijing–Tianjin–Hebei (BTH), the most polluted area in China. Our results show that exports contributed 55–62% of BTH's production emissions and 54% of its total value added. BTH's large exports of metals and metal products, nonmetal mineral products, chemical and transportation and warehousing, generated a larger share of pollutant emissions (36–46% of BTH's total) than that of value added (17%) along the supply chain. Most of BTH's embodied emissions in exports go to neighboring provinces and the developed east coastal regions in China, although the economic returns are comparatively low. Among BTH, industrial production in Beijing and Tianjin lead to more pollutant emission than value added in Hebei, due to reliance on pollution-intensive product imports from Hebei. Our results call for refocusing and restructuring of BTH's industry and trade structures to balance the economic gains and environmental losses for each region.

1. Introduction

With the increasing concern over atmospheric pollution and associated health impacts [1], pollution mitigation has become a top priority of the central and local government in China. To improve air quality, the central government implemented the "Action Plan for Air Pollution Control" (hereafter referred to as Action Plan) in September 2013 [2]. In this plan, China's most polluted area, Beijing–Tianjin–Hebei (BTH), was required to reduce its concentration of fine particulate matter ($PM_{2.5}$) by 25% in 2017 compared to its 2013 levels (88.3 $\mu g/m^3$ for Beijing, 112.7 $\mu g/m^3$ for Tianjin and 112.9 $\mu g/m^3$ for Hebei [3]). In response, local governments have released detailed plans for regional mitigation actions, ranging from end-of-pipe control to closing, restructuring

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* Corresponding authors.
E-mail addresses: qiangzhang@tsinghua.edu.cn (Q. Zhang), hhuo@tsinghua.edu.cn (H. Huo).

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and relocating factories [4]. These place great pressure on BTH and would bring heavy economic losses due to considerable investment and capacity reduction [5].

In the past few years, BTH has been one of the most important industrial area in China and provided abundant industrial products for other regions of China and other countries. For example, in 2010, BTH accounted for 27% and 8% of China's total steel and cement production, respectively [6]; these comprised 17% and 3% of BTH's total industrial output [7]. However, these pillar industries also brought heavy atmospheric pollution. In 2013, BTH's annual average $PM_{2.5}$ concentration reached 106 $\mu g/m^3$ [8]; 52% of this pollution came from the industrial sectors [9] (44% from industrial production and 8% from power sector), and steel and cement contributed 40% and 11% to the total primary $PM_{2.5}$ emissions from industrial production, respectively, based on the calculation results of the Multi-resolution Emission Inventory for China (MEIC model: http://www.meicmodel.org).

As the most important driving force for local production, exports and their contribution to local environmental impacts have been widely studied, including the socioeconomic [10–12] and ecological impacts [13] as well as greenhouse gas emissions [14–18] and water consumption [19–21]. Recently, with the increasing concern over the severe atmospheric pollution in China, exports and associated pollutant emissions have been studied extensively [22–28]. Zhao et.al estimated that in 2007, exports accounted for 15–23% of China's $PM_{2.5}$ and related precursor emissions [26], and comprised 15% (8.3 $\mu g/m^3$) of the Chinese population-weighted $PM_{2.5}$ concentration [25]. Trade adjustment should be a key aspect of China's actions towards pollution mitigation.

However, production for exports creates employment opportunities and, hence, income [29]. For example, in 2013, exports accounted for 24% of China's total gross output [30]. They have become an important way to promote economic growth and thus improve living standards, which are critical components of social development. Given the equal importance of environmental protection and economic growth to social development and the significant role of exports in both the environment and economy, policymakers must give full consideration to develop, enforce and maintain environmentally friendly trade adjustment policies. Recently, a few studies focusing on trade-related problems were conducted from a tradeoff perspective [29,31–33]. For example, Simas et al. [29] analyzed international trade and its impact on local employment creation, as well as energy consumption and greenhouse gases, and they found that even though the developed countries have been net importers with various negative impacts on developing regions, simply reducing their import trade volume could lead to more unemployment in developing regions, especially for the poorer households [11]. Due to the prominence of Chinese exports, Tang et al. [33] analyzed China's energy consumption and employment creation induced by international exports. They found that the energy-intensive exports happen to be in labor-intensive sectors. Hence, when making trade adjustments, policy makers must pay close attention trade to the relative social and economic impacts. In recent years, atmospheric pollution mitigation has been a top priority of central and local governments, export-related strategies attract increasing concern [23,25–27]; however, to our knowledge, analyses of the trade-off analysis are absent to date. Moreover, pollutant emissions characteristics vary greatly across regions and sectors due to significant disparities in stage of development, industrial structure, energy mix and pollution control technology [34–38]. Thus, quantitative region- and sector-specific analysis on the balance or unbalance between economic gains and environmental losses due to trade is critical for designing social development strategies. Further, atmospheric pollution is regionally oriented, an environment-economic tradeoff analysis for regional exports will be critical for regional trade adjustment, especially for those heavily polluted regions.

In this study, we quantified BTH's export-related emissions and economic gains on a sectoral basis for 2010. Additionally, since great trade flows existed between Beijing, Tianjin and Hebei, we also analyzed the cross-regional impacts induced by trade between the three provinces. We examined emissions of carbon dioxide (CO_2), $PM_{2.5}$ and PM precursors (sulfur dioxide (SO_2), nitrogen oxide (NO_x), and non-methane volatile organic compounds (NMVOC)). The $PM_{2.5}$ and its precursors are examined because of their great impact on human health [39–41]. CO_2 emissions are also included because they have the same emission sources as atmospheric pollutant emissions, and various studies have talked about co-benefit of mitigation [37,42–44]; further the 12th Five-Year Plan has assigned the most ambitious goals to reduce greenhouse gas intensity in BTH (i.e., 18% for Tianjin, 17% for Beijing and Hebei, and 10–18% for other provinces) [45]. From an economic aspect, we mainly consider the value added (also known as gross domestic product) because of its versatility [46].

2. Method and data

2.1. Input–output model

The environmental and socioeconomic impacts of a specific product or service include all direct and indirect impacts generated along the production chain [47]. The input–output model, developed by Leontief [48], captures the interconnections among sectors and regions, and has been widely used to trace various impacts along the production chain of a finished product [49]. In this study, we extract a three-region input–output table for BTH based on the latest Chinese multi-regional input–output table for 2010 compiled by Liu et al. [7]. The previous model of Liu et al. [50] for 2007 has been widely used for various studies [15,19,20,26,51,52]. Here, our three-region model for BTH includes detailed information for 30 sectors of interprovincial trade and international export. The model structure is presented in Table A1. The monetary flow balance in each row can be written as:

$$\sum_{s=1}^{3}\sum_{j=1}^{30} z_{ij}^{rs} + \sum_{s=1}^{3} y_i^{rs} + \sum_{t=1}^{28} e_i^{rt} = x_i^r \tag{1}$$

Here, z_{ij}^{rs} indicates cross-regional industrial demand from sector i in province r to sector j in province s; y_i^{rs} indicates finished products of sector i produced in province r and consumed in province s; e_i^{rt} means exports from sector i in province r to the other 27 provinces in China and other countries; x_i^r indicates total output of sector i in region r.

According to the input–output model [48], input coefficient from sector i in province r to produce unit output for sector j in province s can be written as:

$$a_{ij}^{rs} = z_{ij}^{rs}/x_j^s \tag{2}$$

Combining Eq. (2) with Eq. (1) and subsequently Eq. (3) gives the following:

$$Ax + y + e = x \tag{3}$$

Here $y = \sum_{s=1}^{3} y^{\bullet s}$ and $e = \sum_{t=1}^{28} e^{\bullet t}$.

Solving for total output, Eq. (3) can yield the following:

$$x = (I - A)^{-1}(y + e) \tag{4}$$

where $(I–A)^{-1}$ is the Leontief inverse matrix, it captures both direct and indirect economic inputs to satisfy one unit of finished or exported products in monetary value; I is identity matrix with ones for the diagonal and zeros for the off-diagonal elements.

Then, pollutant emissions (p) and (a) value added induced by exported products can be calculated as:

$$p = \hat{f}(I - A)^{-1}e \tag{5}$$

$$a = \hat{v}(I - A)^{-1}e \tag{6}$$

Here f is province- and sector-specific pollutant emission intensity vector and v is value added coefficient vector in BTH, respectively. $\hat{f}$ and $\hat{v}$ represent the diagonalization of f and v.

Emissions and value added induced by export from BTH to a specific region t can be written as:

$$p^{et} = \hat{f}(I - A)^{-1}e^{\bullet t} \tag{7}$$

$$a^{et} = \hat{v}(I - A)^{-1}e^{\bullet t} \tag{8}$$

Sector-specific results can be obtained by replacing $e^{\bullet t}$ in Eqs. (7) and (8) with $e_j^{\bullet t}$, which denotes column vector that only contains export volume from sector j, with values for all other sectors zeroed out. Note that our calculation matrix retains regional differences among Beijing, Tianjin and Hebei. To analyze the other regions' impact on BTH, we aggregate our results based on the average results for BTH as we regard BTH as an integral whole.

For the cross provincial impacts between Beijing, Tianjin and Hebei, the calculation formulae can be written as:

$$p^{rs} = \hat{f}(I - A)^{-1}y^{rs} \tag{9}$$

$$a^{rs} = \hat{v}(I - A)^{-1}y^{rs} \tag{10}$$

y^{rs} indicates province r's finished products exported to province s, and p^{rs} and a^{rs} indicate region r's emissions and the value added induced by these exports.

2.2. Data for production-based pollutant emissions

We use sector-specific emission inventories for Beijing, Tianjin and Hebei in 2010 from the publicly available MEIC model. MEIC is a unit/technology-based, bottom-up air pollutant emission inventory developed by Tsinghua University. It covers 10 pollutants (SO_2, NO_x, $PM_{2.5}$, NH_3, CO, BC, OC, VOC, PM10, and PMcoarse) and CO_2 for ~700 anthropogenic emission sources. Detailed inventory methodology is available on the MEIC web (http://www.meic-model.org/methodology.html). Further, as the emission data are only available at the aggregated industrial sector level, we use regional energy balance table [53] and the sector-specific energy consumption data [54–56] for 2010 to split emissions by specific energy consumption into 30 sectors, which are defined in the MRIO model. Detailed information for MEIC and the mapping process from inventory sectors to traditional economic sectors can be found in our previous studies [22,24]. In addition, pollutant emissions from direct residential energy use are not included in this study, as we assume that these emissions are not directly related to economic activities.

The value added of each sector in BTH are generated from the multi-regional input–output model, as shown in Table A1. They consist of fixed asset depreciation, payment for labor and tax and operating surplus. Here we aggregate these values and do not distinguish the sub items' impacts.

3. Results

3.1. Pollutant emissions and economic gains from BTH's production and exports

Based on the MEIC model, in 2010, industrial production and associated economic activities (e.g., power generation and transportation) in BTH contributed 1.8 Tg SO_2, 2.8 Tg NO_x, 0.8Tg primary $PM_{2.5}$, 1.5Tg NMVOC and 913.3 Tg CO_2 emissions (Fig. 1a), accounting for 7–10% of the national total; the relative value added was 4365 billion yuan, accounting for a similar contribution ratio (10%) to the national total. This means that the BTH area achieved the national average for economic-environment efficiency (GDP per unit emissions) in 2010. However, of the total emissions in BTH, 78% of SO_2, 73% of NO_x, 80% of $PM_{2.5}$, 58% of NMVOC, and 75% of CO_2 occurred in Hebei, although Hebei's value added only accounted for 48% of BTH's total (Fig. 1a). Therefore, Hebei's economic-environment efficiency is far below the regional average level.

Production in BTH supplies three consumption categories: local consumption, interprovincial export and international export. Fig. 1b compares the contributions of these three categories to BTH's pollutant emissions and value added. Interprovincial export is the largest contributor to the total emissions, accounting for 50% of BTH's total SO_2 emissions, 45% of NO_x, 52% of $PM_{2.5}$, 48% of NMVOC and 49% of CO_2. Local consumption contributed 40% to the total SO_2 emissions, 45% to NO_x, 38% to $PM_{2.5}$, 38% to NMVOC and 41% to CO_2. However, from the economic aspect, local consumption contributed 46% of BTH's total value added in 2010, which is higher than that of interprovincial export (42%). International export contributed 12% of BTH's value added and 10–14% to BTH's emissions. These shares are less than those of national average (17–36%) shown in Lin et al. [23], suggesting that BTH was far more influenced by domestic demands. As discussed above, exports from BTH generated more atmospheric pollutants than local consumption did for unit economic returns, therefore, BTH's export structure may not be optimal in terms of the economy environment balance.

3.2. Pollutant emissions versus economic gains generated by sector-specific exports from BTH

Table 1 shows sectoral composition of international and interprovincial exports from BTH, and embodied value added and pollutant emissions per 1000 yuan of exports for each sector (sector aggregation is shown in Table A2). In 2010, metal and metal products, equipment manufacturing and the service sectors dominated BTH's exports, which together accounted for 64% of BTH's total export volume. However, because of the great differences in production process, energy use, and material input, sectoral contributions to BTH's value added and pollutant emissions per unit of exports vary significantly.

From the economic aspect, the wholesale, retail, catering and accommodation and other service sectors captured relatively higher value added per unit of exports (786 and 723 yuan per 1000 yuan exports) because they rely highly on technology or service innovations, while manufacturing industries captured much less value added per unit of exports (507–606 yuan per 1000 yuan of exports) due to intensive interaction and material exchanges with other sectors or other regions [57]. For example, although equipment manufactures were often regarded as "high-technology", they only obtained 507 yuan per 1000 yuan of exports. Similarly, the data for metal and metal products is 569 yuan per 1000 yuan of exports. It is notable that the agriculture and mining sectors have shown higher value added coefficients (808 and

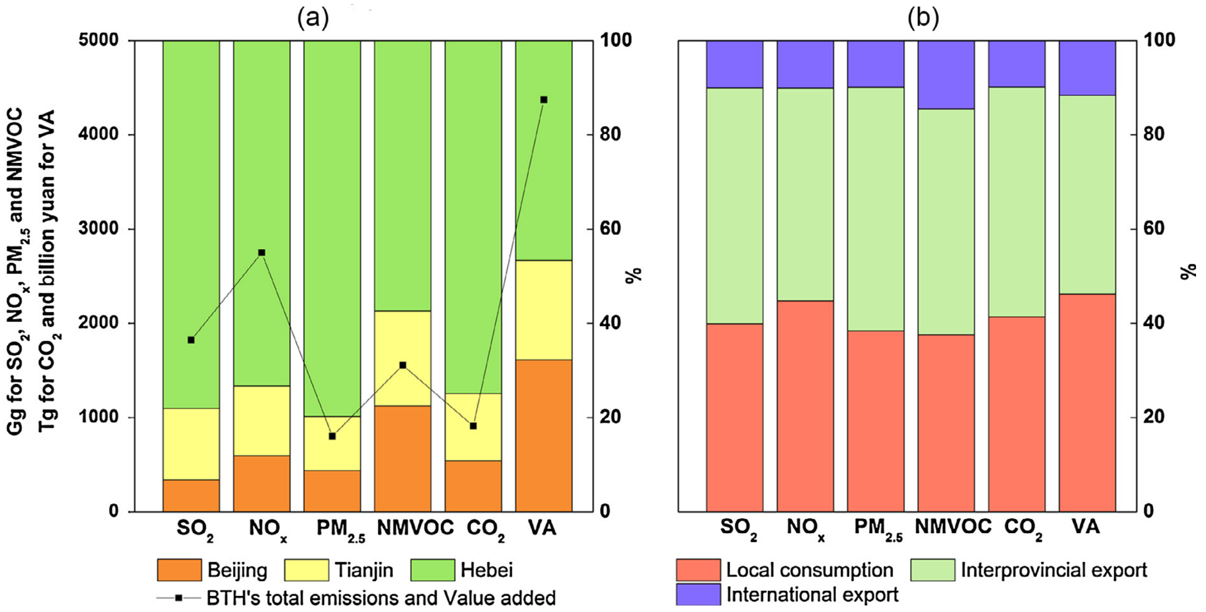

Fig. 1. (a) Regional contributions to BTH's pollutant emissions and value added; (b) the contribution of consumption categories to BTH's production-based emissions and value added.

Table 1
Export structure of BTH and domestic value added and emissions generated per 10^3 yuan exports by sector.

Sectors	Export volume composition (billion yuan, %)		Value added and pollutant emissions generated per 10^3 yuan of exports for each sector (Yuan/10^3 yuan, kg/10^3 yuan, Mg/10^3 yuan for CO_2)					
	International	Interprovincial	Value added	SO_2	NO_x	$PM_{2.5}$	NMVOC	CO_2
1. Agriculture	0.6 (0.6)	17.4 (6.1)	808	0.15	0.28	0.05	0.23	0.57
2. Mining	1.2 (1.4)	16.7 (5.8)	821	0.15	0.23	0.05	0.22	0.74
3. Food products	1.3 (1.5)	11.5 (4.0)	606	0.29	0.30	0.06	0.19	0.83
4. Textile and clothing	4.0 (4.6)	6.7 (2.4)	592	0.28	0.31	0.05	0.24	0.86
5. Wood, furniture, paper and printing	1.4 (1.7)	4.6 (1.6)	565	0.54	0.44	0.08	0.49	1.31
6. Chemicals	8.1 (9.5)	23.6 (8.2)	541	0.48	0.44	0.16	1.08	1.43
7. Nonmetal mineral products	1.4 (1.6)	5.1 (1.8)	591	0.79	1.46	0.77	0.43	6.42
8. Metals and metal products	8.5 (9.9)	59.3 (20.7)	569	0.68	0.74	0.36	0.17	3.59
9. Equipment manufactures	27.2 (31.7)	47.6 (16.6)	507	0.17	0.23	0.07	0.14	0.83
10. Other manufactures	2.6 (3.0)	1.9 (0.7)	548	0.12	0.17	0.04	0.08	0.57
11. Electricity, heat, gas and water supply	0 (0)	0.2 (0.1)	614	1.46	2.55	0.26	0.14	7.50
12. Construction	1.4 (1.6)	0.8 (0.3)	569	0.26	0.47	0.16	0.26	1.62
13. Transport and warehousing	5.1 (5.9)	17.5 (6.1)	672	0.22	1.13	0.13	0.45	1.78
14. Wholesale, retail, catering and accommodation	9.0 (10.5)	14.2 (5.0)	786	0.09	0.14	0.04	0.08	0.43
15. Other service sectors	14.1 (16.4)	59.0 (20.6)	723	0.09	0.14	0.04	0.11	0.47
16. Average			630	0.30	0.41	0.13	0.26	1.44

821 yuan per 1000 yuan of exports, respectively), which are not because advanced technologies were involved in these sectors but because they are labor intensive and relied relatively little on intermediate input.

In contrast to the economic returns, the pollutant emissions triggered by exports are mainly from primary manufacturing (column 4–8 in Table 1). As the major export sectors of BTH, chemicals, metals and metal products contributed the highest SO_2 and NO_x emissions per unit of exports. In addition, because of the high NMVOC emissions involved in the production of chemical products, such as polystyrene, tyres and paints [58], their exports also triggered the highest NMVOC emissions per unit of exports (1.08 kg NMVOC per 1000 yuan exports). Nonmetal mineral products have the highest primary $PM_{2.5}$ emissions level per unit exports (0.77 kg per 1000 yuan exports) owing to their high process emissions, such as those from the calcination and grinding involved in cement production. For the "high-technology" equipment manufacturing and other manufacturing, pollutant emissions for unit exports are rather small, just over half of BTH's average. As expected, wholesale, retail, catering and accommodation and other service sectors have relatively low emissions per unit exports.

Fig. 2 illustrates the sectoral contributions to BTH's total value added from supply chain perspective and the associated emissions per unit of value added. In 2010, exports contributed 2343 billion yuan (54%) to BTH's total value added. Of this, 30% (711 billion yuan) was from less pollution-intensive service sectors (7.8% from the wholesale, retail, catering and accommodation and 22.5% from the other service sectors), 16% was from the high pollution-intensive metals and metal products, and another 16% was from the equipment manufacturing. However, from the emission perspective, metal and metal products contributed 33–49% to BTH's exported SO_2, NO_x, primary $PM_{2.5}$ and CO_2 emissions; service

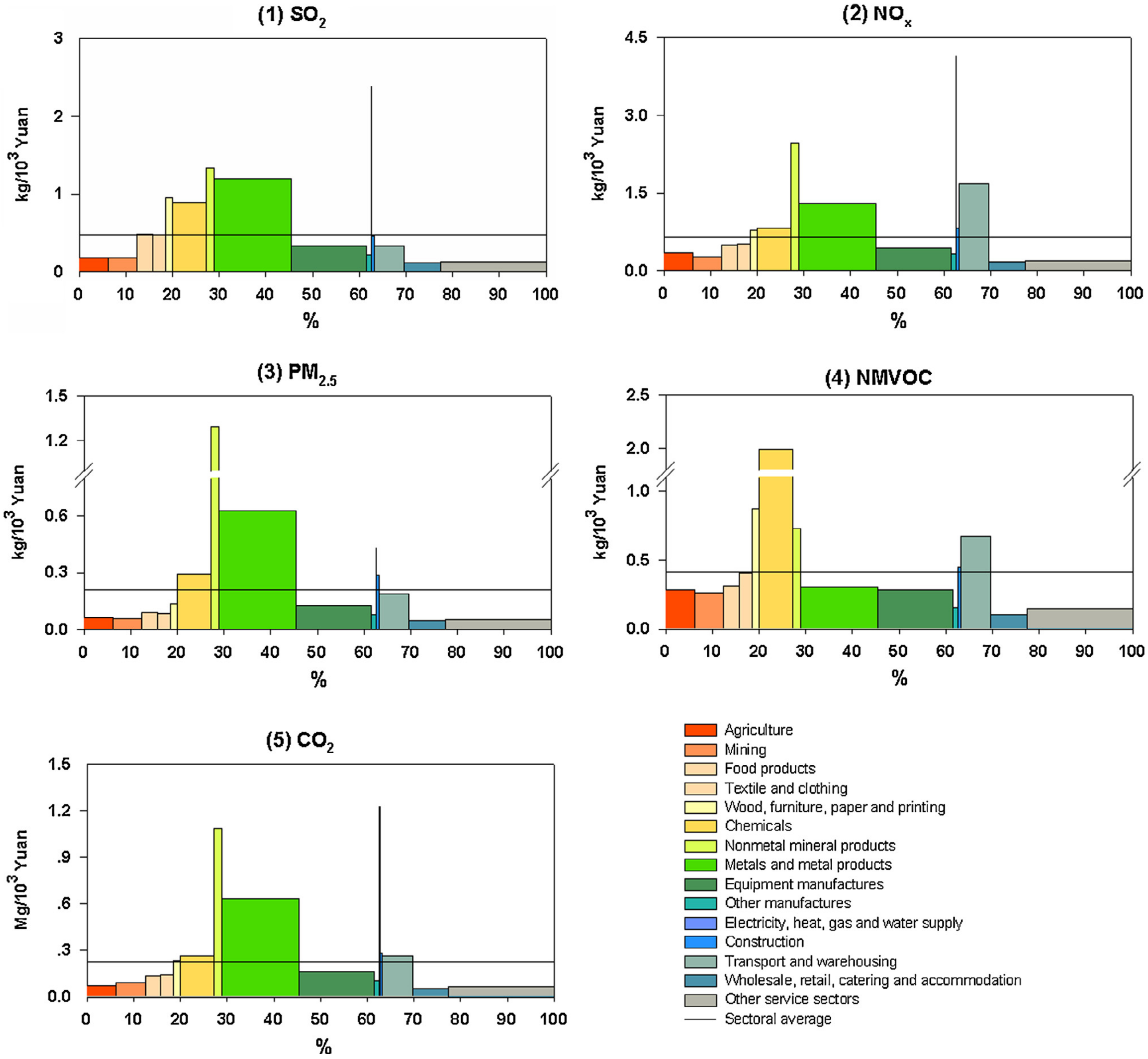

Fig. 2. Emission intensities (*g* of pollutant/value added) of BTH's exports by sector from the supply chain perspective. The *Y*-axis represents the emission intensity of units value added created by exports from each sector. The *X*-axis represents the accumulative export-related value added contributions by sector.

sectors and equipment manufacturing only contributed 7–10% and 10–12% to the total exported emissions. Therefore, BTH's production of metal and metal products for export at the expense of the environment may not be desirable. In addition, exports of the chemicals and nonmetal mineral products are also pollution-prone, as their pollutant emissions per unit value added are 1.2–4.9 times and 1.8–6.1 times the average intensity across all sectors, respectively. Moreover, as important sectors in trade, transportation and warehousing contributed 17% and 11% of BTH's export-related NO_x and NMVOC emissions, and the pollutant emissions per value added were 2.6 and 1.6 times the sectoral average, respectively, owing to the high emission factors of diesel transportation vehicles [24].

3.3. Exports related pollutant emissions and value added driven by region

Taking SO_2 as an example, Fig. 3 demonstrates the impacts of individual region on BTH's pollutant emissions and economy by importing products from BTH. Fig. 3 also presents the sectoral composition for selected regions. Data for other pollutants can be found in Table S1, and abbreviation for the regions are provided in Table A3.

Geographically, most of BTH's emissions and value added embodied in exports go to southern developed provinces and BTH's neighboring regions. The most developed regions, such as Jiangsu, Zhejiang and Shanghai (the so called Yangtze River Delta, YRD), outsourced 136, 115 and 64 Gg of SO_2 to BTH through trade in 2010, respectively, together accounting for 17.2% of BTH's total SO_2 emissions; however, their value added contribution was only 14.1%. The difference between economic and emission contribution ratios is partly due to large share of pollution-intensive metal and metal products, which contributed 49% of emissions and 26% of value added related to those exported from BTH to YRD. A driver of the high ratio from this sector may be the 2010 World Exposition (EXPO), which was held in Shanghai, and a large amount of building materials were needed to supply the demand for constructing buildings and infrastructure around YRD. In addition,

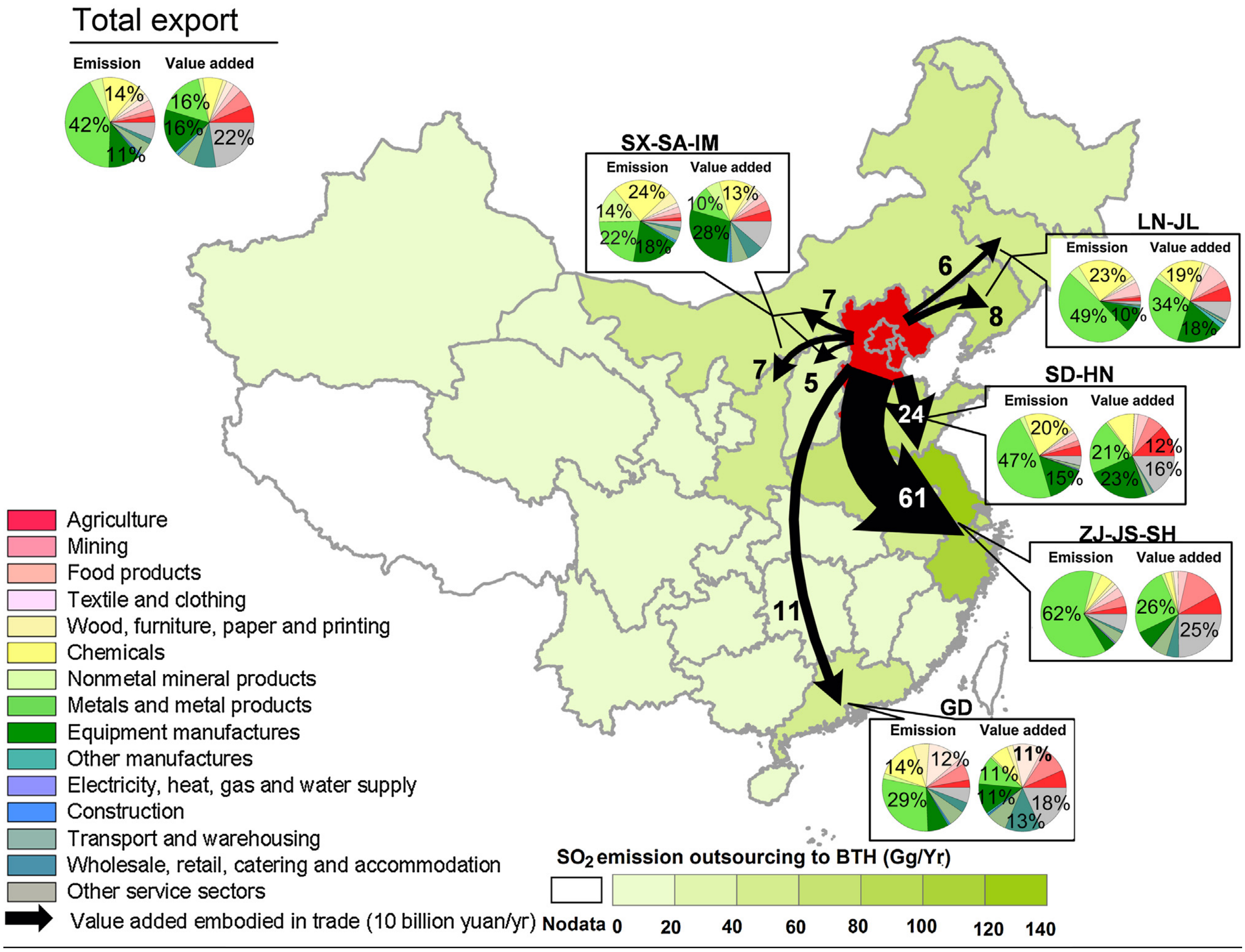

Fig. 3. BTH's pollutant emissions and value added generated by interprovincial exports and the sectoral composition. The shading in each region indicates the related emissions outsourced to BTH; the thickness of the black arrow indicates associated value added embodied in exports.

Guangdong, a highly developed southern province characterized by clothing manufacturing, contributed 46 Gg (2.5% of BTH's total) to BTH's SO_2 emissions. In addition to metals and metal products, Guangdong also imported many textile and clothing products to support its clothing industry. Furthermore, as the national capital region, BTH also provided several types of services, such as education, financial services and public management to Guangdong. These contributed to 26% of the total exports to Guangdong. Consequently, Guangdong's imports contributed similar shares to BTH's total value added (2.5%) and emissions (2.5%).

Compared with developed regions, neighbors of BTH contributed relatively less to BTH pollutant emissions because they have abundant resources to meet their own needs, and they mainly serve as net exporters in trade [26]. Henan, Shandong, Shanxi, Shannxi, Inner Mongolia, Liaoning and Jilin in total outsourced 347 Gg (19% of the total) SO_2 emissions to BTH through trade, which was similar to the sum from YRD and Guangdong (361 Gg, 20%); however, their contribution to BTH's value added was only 571 billion yuan (13.1% of the total), which is less than the sum of YRD and Guangdong (723 billion yuan, 16.6%). The low economic-environment efficiency for trade with these regions is mainly due to the high percentage of imports of nonmetal mineral products, as well as metal and metal products and chemical products imports. Note that for BTH, the ratio of pollutant emissions to value added for nonmetal mineral products (13 kg/1000 yuan) is 4 times the average level of all other sectors, and is even greater than that for metal and metal products (12 kg/1000 yuan).

For the surrounding regions of BTH, their import structures from BTH vary markedly due to a combination of the difference in the regional stage of development and product attributes. For example, in addition to metal and metal products, Shaanxi, Shanxi and Inner Mongolia also imported large quantities of nonmetal mineral products to support their infrastructure investment. The latter contributed 14% to their total imported SO_2 emissions from BTH but only accounted for 6% of the relative value added. Furthermore, nonmetal mineral products mainly consist of cement, brick and lime-stone, and their prices per unit of mass are relatively low; therefore, they would not be transported too far due to the high transportation fees. In Shandong and Henan, increasing construction and advanced manufacturing, coupled with the lack of locally manufactured steel, have forced them to import large amounts of metal and metal products to support their industrialization and construction. In 2010, metal and metal products

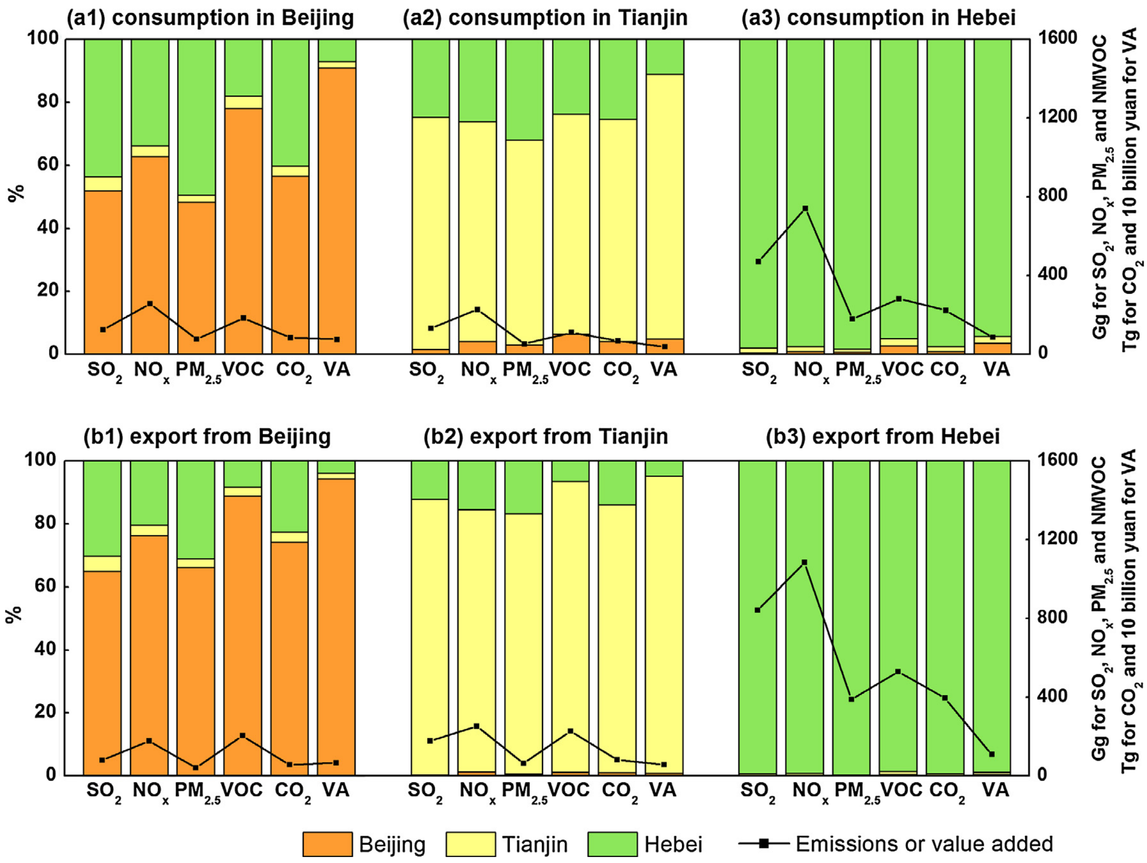

Fig. 4. BTH's pollutant emissions and value added generated by consumption and exports of each region, and where the production occurred.

accounted for 22% of their import volume from BTH, which contributed 47% to their total imported SO_2 emissions and 21% of the relative value added.

3.4. Impacts of trade within BTH

Due to close economic linkage between Beijing, Tianjin and Hebei, production or consumption in one region can also trigger a wide range of production activities in the other two regions and thus cause pollutant emissions as well as economic benefits there [38]. Fig. 4 shows the consumption and export-related pollutant emissions and value added occurring in each region within BTH.

In 2010, Beijing's consumption triggered 126 Gg SO_2, 258 Gg NO_x, 77 Gg $PM_{2.5}$, 186 Gg NMVOC and 85 Tg CO_2 emissions in BTH, accounting for 7–12% of the total emissions occurring in BTH; furthermore, because Beijing relies on large product imports from Hebei, 18–44% of these emissions occurred in Hebei and another 2–4% occurred in Tianjin. Meanwhile, Beijing's production for exports brought about 4–13% of the total emissions in BTH, and Hebei contributed 8–30% to these emissions. From an economic perspective, Beijing's consumption and production for exports generated 762 and 693 billion yuan, respectively, but Hebei only obtained 54 and 26 billion yuan (7% and 4% of the total relative value added), respectively, by supplying products to Beijing. That is to say, under the current production structure, generating 1 billion yuan in Beijing would result in 0.9Gg SO_2, 2.3 Gg NO_x, 0.5 Gg $PM_{2.5}$, 2.5Gg NMVOC and 0.7 Tg CO_2 emissions in Beijing, and it also produces 0.2–0.8 times these emissions in Hebei but only generates 0.06 billion yuan for Hebei. Compared to Beijing, Tianjin relies relatively less on Hebei because of its convenient water traffic to import from other regions, thus its impact on Hebei is relatively small. In 2010, to support Tianjin's consumption and production for exports, Hebei emitted 54 Gg SO_2, 99 Gg NO_x, 28 Gg PM2.5, 41Gg NMVOC and 28 Tg CO_2, accounting for 13–29% of Tianjin's production emissions; this generated 71 billion yuan for Hebei, only accounting for 8% of Tianjin's GDP that year. Therefore, to support Beijing and Tianjin's economic activities, Hebei is bearing unbalanced pollutant emissions and economic gains.

As the hinterland of Beijing and Tianjin, Hebei acts as a supplier and relies less on supply from Beijing and Tianjin. In 2010, Hebei's consumption and exports contributed 22–27% and 34–48% of the total emissions occurring in BTH, and 97–99% of these emissions were produced by Hebei itself.

4. Discussions

In 2010, production for international and interprovincial exports accounted for 55–62% of BTH's production emissions but comprised 54% of BTH's total gross domestic output. Among its exports, the three most pollution-intensive sectors (metals and metal products, nonmetal mineral products and chemicals) accounted for 49–69% of BTH's export-related pollutant emissions but only contributed 25% to the associated added value. To reduce these unbalanced environmental losses, BTH should focus on reducing these sectors' export volume through industrial upgrading, as well as cleaning the production chains of these sectors.

To clean up its production structure, BTH must begin with cleaning its energy consumption structure [59]. In 2010, BTH's coal consumption accounted for 78% of its total energy consumption (90% for Hebei), which is far more than the national average (69%) [6]. Consequently, coal consumption is responsible for 78%

of BTH's total SO_2 emissions, 53% of NO_x emissions, and 50% of CO_2 emissions (based on data calculation from the MEIC model). Therefore, BTH, especially Hebei, are in urgent need of developing clean energy in addition to the end-of-pipe control technologies. On the one hand, they can clean their energy system by accelerating the process of coal-to-gas and coal-to-electricity projects. These would reduce the dispersed coal combustions, whose pollutant emissions are hard to regulate. On the other hand, they should strengthen renewable energy development, such as wind and solar energy, which are abundant in northern China [60]. For example, in 2013, BTH's wind power generation accounted for 4% of total electricity generation in BTH [61], higher than national average share (2.5%) but far less than that of the European Union (EU, 8%) [62]. In 2013, the price of wind energy for new contracts signed in the United States (US) reached 2.5¢/kWh, less than that of fossil-fuel energy (5¢/kWh for nature gases); and it is estimated that wind energy in the US will account for 20% of its electricity by 2030 [63]. Thus, even though wind energy costs more in China presently (8.6¢/kWh) [64], cost reduction and mass production would be feasible in the near future. In addition, with the fast development of wind or solar energy, construction of auxiliary infrastructure is equally important [65,66]. In 2013, the ratio of wind curtailment in BTH reached ~18% in 2013 (author's calculation) [61,62], thus BTH should also strengthen its construction of power grid transmission lines, simultaneously.

In recent years, China's deteriorating air quality and weakening domestic demands have placed great pressure on its heavy industry areas like BTH. In response to the Action Plan, Hebei, the most important steel industrial base in China, committed to reducing 60 million tons of steel production capacity by 2017, accounting for 10% of Hebei's total steel production in 2014. However, in 2015, the central government implemented the "One Belt, One Road" program, which intended to reenergize central Asia's economy. It will require a significant amount of infrastructure construction, thus providing new opportunities for heavy industry in China. Hence Hebei will undoubtedly play an important role in this program. This provides it with great challenges as well as opportunities to simultaneously balance its economic development and curbing atmospheric pollution. Thus, in addition to eliminating superfluous production capacity and these with backward techniques, Hebei also needs to improve production efficiency, such as promoting the increase of electric arc furnaces in its steel industries, which are considered more energy efficient [67]. Furthermore, to gain more economic returns, Hebei should extend its production chain to promote industrial upgrading. It can introduce more steel-related high-tech industries, such as high-speed rail and subway manufactory.

Within BTH, due to Beijing and Tianjin's great imports from Hebei, promoting industrial development in Beijing and Tianjin lead to higher pollutant emissions in Hebei province. Further, increasing emissions in Hebei would also lead to higher pollution concentration in Beijing and Tianjin to some extent, due atmospheric transport of pollutants across provincial borders [9]. Thus, to promote the joint control of atmospheric pollution in BTH, local governments should cooperate to facilitate BTH's industrial upgrading as a whole. Recently, to improve the atmospheric environment in Beijing and Tianjin, a large number of heavy industry enterprises were transferred to Hebei, which also transferred emissions there. Hence, Beijing and Tianjin are directly and indirectly responsible for environmental deterioration in Hebei. Thus Beijing and Tianjin should help Hebei avoid more pollution by transferring high technologies and providing financial aid or subsidies to Hebei. Simultaneously, Hebei should set stricter emission standards for new entering companies; it can also improve its production technology by merging the advanced technology from new entering companies through initiative and mandated cooperation.

5. Conclusion

With increasing concern over atmospheric pollution, climate change and associated health impacts, the trade-off between environment and the economy for industrial production become a key issue in development strategy of BTH region. This paper is the first attempt to quantify BTH's export-related emissions of atmospheric pollutants (SO_2, NO_x, primary $PM_{2.5}$ and NMVOC) and CO_2 versus the economic gains from a supply chain perspective by conducting an input–output analysis. Our results shown that, due to the dominance of heavy industry in it economic structure, BTH bears more pollutant emission ratio than that of economic gains from product exports. Among regions within BTH, as with different economic roles and development stages, promoting industrial production in Beijing and Tianjin are to some extent lead to increasing pollutant emissions in Hebei. The results of this work would help policy makers better to understand the environmental and economic trade-off from exports, and provide reasonable technical supports for mitigating regional air pollution through industrial upgrading and export adjustment. Moreover, our evaluation process can also be used in other regions experiencing similar problems.

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Appendix A.

See Tables A1–A3.

Appendix B. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.apenergy.2016.04.038.

Table A1
Three region input–output table for BTH.

	Beijing	Tianjin	Hebei	Final demand			Interprovincial export			International exports	Total outputs
				Beijing	Tianjin	Hebei	Shanxi	...	Xinjiang		
Beijing	*Z*			*Y*			*Ex*				*x*
Tianjin											
Hebei											
Value added	*v*										
Total outputs	*x'*										

Table A2
Sector classifications.

Sector ID	Aggregated sectors	Sector ID	MRIO sectors
1	Agriculture	1	Agriculture
2	Mining	2	Coal mining and processing
		3	Crude petroleum and natural gas products
		4	Metal ore mining
		5	Non-ferrous mineral mining
3	Food products	6	Manufacture of food products and tobacco processing
4	Textile and clothing	7	Textile goods
		8	Apparel, leather, furs, down and related products
5	Wood, furniture, paper and printing	9	Sawmills and furniture
		10	Paper and products, printing and record medium reproduction
6	Chemicals	11	Petroleum processing and coking
		12	Chemicals
7	Nonmetal mineral products	13	Nonmetal mineral products
8	Metals and metal products	14	Metals smelting and pressing
		15	Metal products
		16	Machinery and equipment
9	Equipment manufactures	17	Transport equipment
		18	Electric equipment and machinery
		19	Electronic and telecommunication equipment
10	Other manufactures	20	Instruments, meters, cultural and office machinery
		21	Handicrafts and other manufacturing
11	Electricity, heat, gas and water supply	22	Electricity, steam and hot water production and supply
		23	Gas and water production and supply
12	Construction	24	Construction
13	Transport and warehousing	25	Transport and warehousing, post and telecommunication
14	Wholesale, retail, catering and accommodation	26	Wholesale and retail trade
		27	Accommodation and restaurants
15	Other service sectors	28	Tenancy and business services
		29	Research and development
		30	Other sectors

Table A3
Provincial abbreviations.

Name	Abb.	Name	Abb.	Name	Abb.
Beijing	BJ	Zhejiang	ZJ	Hainan	HI
Tianjin	TJ	Anhui	AH	Chongqing	CQ
Hebei	HB	Fujian	FJ	Sichuan	SC
Shanxi	SX	Jiangxi	JX	Guizhou	GZ
Inner Mongolia	IM	Shandong	SD	Yunnan	YN
Liaoning	LN	Henan	HN	Shaanxi	SA
Jilin	JL	Hubei	HU	Gansu	GS
Heilongjiang	HL	Hunan	HA	Qinghai	QH
Shanghai	SH	Guangdong	GD	Ningxia	NX
Jiangsu	JS	Guangxi	GX	Xinjiang	XJ

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