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Research article

Re-examining the embodied air pollutants in Chinese exports

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ABSTRACT

China is the world's largest exporter and may release lots of air pollutants to produce exported commodities due to taking coal as its main source of energy. Processing exports play a significant role in Chinese exports, yet previous studies of embodied air pollutants in Chinese exports failed to distinguish processing exports from normal exports. This paper investigates the effect of trade heterogeneity on the estimation of embodied emissions by re-examining the embodied air pollutants in Chinese exports based on an extended non-competitive input-output table that distinguishes processing from normal exports. The results show that processing exports generate 22.81% of the value added embodied in gross exports and 16.48% of the emissions embodied in gross exports. The embodied air pollutants in Chinese exports would be overestimated by 12%–22% without accounting for trade heterogeneity. Unequal distributions of export-related air pollutants and value added exist among different sectors. In particular, Manufacturing of Electronics and Communication Equipment sector induces 39.56% of embodied emissions in processing exports, and 41.78% of which are generated by Production and Supply of Electric Power and Steam Hot Water sector. China's restrictions on processing exports should focus not only on the direct emissions generated by each sector but also on the emissions embodied in domestic supply chains.

1. Introduction

China is the world's largest exporter. In order to produce exported commodities, China may release lots of pollutants due to taking coal as its main source of energy and become a pollution haven for developed countries (Cole, 2004). Evaluating the embodied air pollutants in exports is important for pollution control in China (Zhang et al., 2018). Most assessment studies have adopted input-output models and these models generally assume that the exported commodities of each industry are homogeneous and thus provide a simple way to trace air pollutants embodied in Chinese exports. However, the production structure of processing exports, accounting for 42% of Chinese gross exports in2012,[1] is different from that of normal exports. Studies of the air pollutants embodied in Chinese exports may yield biased results if trade heterogeneity is not taken into account. To solve this problem, this paper re-examines embodied air pollutants in Chinese exports based on an extended non-competitive input-output table that differentiates processing from normal exports.

We separate between processing exports and normal exports for four reasons. First, processing trade plays an important role in China. The scale of processing exports reached a peak of $US 863 billion in2012[2] (see Appendix A). Second, the production structure of processing exports is quite different from normal exports. Normal exports refer to the processing of domestic raw materials and other intermediates inputs into finished products for export. Processing exports import raw materials, parts and components from abroad and process them into finished products for export (Jiang et al., 2016). Third, the Chinese government implements more tightly controls on processing exports than normal exports. In order to avoid developed countries outsourcing pollution-intensive production stages to China, some high energy-consuming and high-pollution products, such as waste electromechanical products, alumina and iron ore, are listed in the catalogues of processing trade prohibition. The Ministry of Commerce and relevant departments are gradually supplementing the catalogue of processing trade prohibition. In addition, Dietzenbacher et al. (2012) found that embodied carbon emissions in Chinese exports would be overestimated

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[1] Source: the data is obtained from Ministry of Commerce of the People's Republic of China. Available at: http://zhs.mofcom.gov.cn/article/Nocategory/201304/20130400107790.shtml.

[2] Source: the data is obtained from National Economic and Social Development Statistics Bulletin for 2012. Available at: http://www.stats.gov.cn/tjsj/tjgb/ndtjgb/qgndtjgb/201302/t20130221_30027.html.

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by 60% without taking trade heterogeneity into account. This finding suggests that previous studies of the environmental impacts generated by Chinese exports may have yielded biased results if they failed to distinguish between normal and processing exports. Therefore, it is necessary to separate between processing and normal exports when examine embodied air pollutants in Chinese exports.

The distinguish between normal and processing exports is not a general problem for all countries. It is a special problem for labor-intensive developing countries such as China and Mexico with export-oriented processing industry economy. And the problem is particularly prominent in China which is located at the downstream of global supply chains and is described as the world factory. It is not a problem for developed countries such as United States and Japan, which are located in the upstream of global supply chains. So this study mainly focuses on the embodied air pollutants in Chinese exports.

This paper builds on a growing literature that indicates it is necessary to distinguish between normal and processing exports in China (Duan et al., 2018; Koopman et al., 2012; Manova and Yu, 2016; Xing, 2018; Yang et al., 2015). For instance, Duan et al. (2018) measured Chinese vertical specialization shares by distinguishing processing export production from other production. Koopman et al. (2012) estimated the domestic content in exports when processing trade is dominant, and Manova and Yu (2016) examined how financial frictions affect company choices between processing and normal trade. With the extension of research on processing exports and public concern regarding environmental issues in China, the effects of processing exports on embodied pollutants in Chinese exports have attracted considerable attention in recent years.

Existing studies on the environmental impacts associated with export production cover carbon emissions (Long et al., 2018; Peters and Hertwich, 2008; Tang et al., 2017; Zhao et al., 2015), air pollutants (Yang et al., 2018; Zhao et al., 2016; Zhang et al., 2017), and water use (Yu et al., 2010, 2014; Zhao et al., 2010, 2018). However, most previous studies ignored the distinction between normal and processing exports except for several studies on carbon emissions (Dietzenbacher et al., 2012; Jiang et al., 2016; Su and Ang, 2013; Su and Thomson, 2016; Xia et al., 2015). For example, Su and Ang (2013) analyze China's carbon emissions embodied in both normal and processing exports, finding that estimation of carbon emissions embodied in Chinese exports would drop by 32% when accounting for trade heterogeneity. The literature finds that approximately 30–42% of Chinese air pollutants are associated with exports (Meng et al., 2016; Liu et al., 2017). However, the existing literature adopts the homogeneity assumption and fails to take trade heterogeneity into account. To the best of our knowledge, this paper is the first to calculate the embodied air pollutants in Chinese exports by accounting for trade heterogeneity.

The remainder of this paper is structured as follows. Section 2 introduces the methodology and data sources of the paper while section 3 presents the results of embodied air pollutants in Chinese exports. Finally, conclusions and policy implications are given in section 4.

2. Methodology and data

2.1. An extended input-output table that captures processing exports

The literature divides input-output tables into competitive and non-competitive input-output tables (see Appendix B). The former assumes that domestic and imported products can be mutually substituted. The latter assumes that domestic and imported products cannot be replaced by each other due to their different properties. Although non-competitive input-output tables reflect the incomplete substitution of domestic goods and imported goods, they fail to capture trade heterogeneity. This paper constructs an extended non-competitive input-output table that distinguishes between processing and normal exports. The differences between the competitive and non-competitive input-output tables and the extended non-competitive input-output table that captures processing exports are shown in Table 1.

This study is based on the extended non-competitive input-output table that captures processing exports. As shown in Table 2, the extended input-output table is a tripartite table distinguishing production for domestic purposes only (class D), production for processing exports (class$P$) and production for normal exports, including the production of non-processing exports and production by foreign-invested enterprises for domestic purposes (class N). The descriptions of the related symbols in this section are presented in Appendix table C1.

We assume that there are n sectors. In this table, $\mathbf{Z}$ is the intermediate use matrix, and $\mathbf{Z}^{DP}$ represents the intermediate input of class D consumed by class$P$. The element z_{ij}^{RS} in $\mathbf{Z}$ refers to the input of sector i in class R that is consumed by sector j in class S, where $i,j \in 1,2\cdots n$. $R,S \in D,P,N$. $\mathbf{x}$ denotes the total output vector, and the element x_j^S in $\mathbf{x}$ represents the total output of sector j in class S. The direct input coefficient a_{ij}^{RS} can be obtained by $a_{ij}^{RS} = z_{ij}^{RS}/x_j^S$. $\mathbf{A} = (a_{ij}^{RS})_{3n\times 3n}$ is the direct input coefficient matrix. The Leontief inverse matrix can be expressed as:

$$\mathbf{B} = (\mathbf{I} - \mathbf{A})^{-1} \tag{1}$$

$\mathbf{y}$ is the final demand vector and $\mathbf{y}^D$ and $\mathbf{y}^N$ represent the final demands of classes D and N, respectively. The direct emission coefficient of sector i in class R is calculated by $f_i^R = q_i^R/x_i^R$. q_i^R represents the emissions from sector i in class R, and x_i^R is the total output of sector i in class R. The vector of emission coefficients for class R is $\mathbf{f}^R = (f_i^R)_{n\times 1}$.

The embodied emissions in the domestic final demand (**EED**) are given by

$$\mathbf{EED} = \mathbf{F} \times \mathbf{B} \times \mathbf{Y} \tag{2}$$

where $\mathbf{F} = \begin{bmatrix} \widehat{\mathbf{f}^D} & & \\ & \widehat{\mathbf{f}^P} & \\ & & \widehat{\mathbf{f}^N} \end{bmatrix}_{3n\times 3n}$ is the diagonal matrix of emission coefficients for a given air pollutant. $\widehat{\mathbf{f}^R}$ represents the diagonal matrix obtained from the vector $\mathbf{f}^R$. $\mathbf{Y} = \begin{bmatrix} \widehat{\mathbf{y}^D} & \\ & 0 & \\ & & \widehat{\mathbf{y}^N} \end{bmatrix}_{3n\times 3n}$ denotes the diagonal matrix of the domestic final demand provided by both domestic enterprises ($\mathbf{y}^D$) and foreign-invested enterprises ($\mathbf{y}^N$).

The emissions embodied in normal exports (**EEN**) are given as

$$\mathbf{EEN} = \mathbf{F} \times \mathbf{B} \times \mathbf{EN} \tag{3}$$

where $\mathbf{EN} = \widehat{\mathbf{e}^N}$ is the diagonal matrix of normal exports.

The emissions embodied in processing exports (**EEP**) are given by

$$\mathbf{EEP} = \mathbf{F} \times \mathbf{B} \times \mathbf{EP} \tag{4}$$

where $\mathbf{EP} = \widehat{\mathbf{e}^P}$ is the diagonal matrix of processing exports. The results can be analyzed from both forward and backward perspectives. From the forward perspective, we can examine the air pollutants from each sector driven by Chinese exports; from the backward perspective, we can capture the air pollutants driven by exports from each sector.

Table 1
The differences between the three types of input-output tables.

Classifications of input-output tables	Distinction between domestic products and imported products	Distinction between processing and normal exports
Competitive input-output table	×	×
Non-competitive input-output table	√	×
Extended non-competitive input-output table that captures processing exports	√	√

Table 2
The structure of an extended input-output table that captures processing exports.

Input			Output					
			Intermediate use			Final use		Total output
			D	*P*	*N*	Final demand	Export	
Intermediate input	Domestic products	*D*	$\mathbf{Z}^{DD}$	$\mathbf{Z}^{DP}$	$\mathbf{Z}^{DN}$	$\mathbf{y}^{D}$	0	$\mathbf{x}^{D}$
		P	0	0	0	0	$\mathbf{e}^{P}$	$\mathbf{x}^{P}$
		N	$\mathbf{Z}^{ND}$	$\mathbf{Z}^{NP}$	$\mathbf{Z}^{NN}$	$\mathbf{y}^{N}$	$\mathbf{e}^{N}$	$\mathbf{x}^{N}$
	Import		$\mathbf{M}^{D}$	$\mathbf{M}^{P}$	$\mathbf{M}^{N}$	$\mathbf{y}^{M}$	0	$\mathbf{x}^{M}$
Value added			$\mathbf{v}^{D}$	$\mathbf{v}^{P}$	$\mathbf{v}^{N}$			
Total input			$\mathbf{x}^{D'}$	$\mathbf{x}^{P'}$	$\mathbf{x}^{N'}$			

Notes: D denotes production for domestic use only (class *D*); *P* is production for processing exports (class *P*); and *N* represents production for normal exports (class*N*). Descriptions of the related symbols in this table are presented in Appendix Table C1.

$\mathbf{v}$ is the value added vector, and $\mathbf{V}$ is the diagonal matrix of value added coefficients. The value added embodied in the domestic final demand (**EVD**), normal exports (**EVN**) and processing exports (**EVP**) can be obtained by replacing the diagonal matrix of emission coefficients (**F**) by the diagonal matrix of value added coefficients (**V**) in equations (2)–(4).

2.2. Data

The National Bureau of Statistics of China (NBSC) provides the 2012 benchmark input-output table for China. The table covers 139 sectors (see Table D1 in Appendix D). Based on this benchmark input-output table and customs statistics, we develop a tripartite non-competitive input-output table with a distinction between normal and processing exports. The processing export vector is constructed based on processing export data from China's General Administration of Customs (CGAC). The value added vector of industries producing processing exports is calculated based on the data from foreign-invested enterprises that have export records. The intermediate input matrix is obtained from the import data for processing production and the proportions of products that are from foreign-invested enterprises and Chinese-owned enterprises and supplied to the domestic market. The data are from China's General Administration of Customs (CGAC). The final demand vector is estimated based on the ratio of the products from foreign-invested enterprises (that are used to satisfy the domestic demand) to the products from all enterprises (that are used to satisfy the domestic demand).

The Report on the State of the Environment in China (MEPPRC, 2018) indicated that the number of days with $PM_{2.5}$ and PM_{10} as the chief pollutants accounted for 94.6% of all heavy pollution days in 2017. Particulate matter (PM) is the chief pollutant affecting the urban atmospheric quality in China. SO_2, NO_X and soot are the main precursors of $PM_{2.5}$ (Yao et al., 2002; Wang and Hao, 2012; Wang et al., 2017). Therefore, this paper selects these three air pollutants to track the embodied emissions in Chinese exports. The emissions data for SO_2, NO_X and soot in this study were obtained from the Chinese Academy for Environmental Planning. To synthetically describe embodied air pollutants in normal and processing exports, based on the approach of Zhang et al. (2018), we used the concept of air pollutant equivalents (APE) to combine SO_2, NO_X and soot emissions into one index. The APE conversion coefficients for SO_2, NO_X and soot are 0.95, 0.95 and 2.18, respectively. This paper adopts the APE index to analyze the air pollutants induced by exports.

Corresponding to the tripartite input-output table, the emissions of air pollutants were split into three classes: emissions for domestic use only ($\mathbf{q}^D$), emissions for processing exports ($\mathbf{q}^P$) and emissions for normal exports ($\mathbf{q}^N$). The total emissions $\mathbf{q}$ are obtained from the Chinese Academy of Environmental Planning, where $\mathbf{q} = \mathbf{q}^P + \mathbf{q}^P + \mathbf{q}^N$. $\mathbf{q}^D$, $\mathbf{q}^P$ and $\mathbf{q}^N$ are estimated based on the emission ratio of each class $\mathbf{w}^D$, $\mathbf{w}^P$ and $\mathbf{w}^N$. The emission ratio in each of the three classes is calculated based on the consumption of the corresponding energy sectors, including Coal Mining Products, Oil and Gas Exploration Products, Refined Petroleum and Nuclear Fuel Processed Products, Coking Products, and Gas Production and Supply. The estimated emissions based on the energy sector $g = z \times c \times f/x$ are obtained through the energy sector consumption data from the China Energy Statistical Yearbook and the intermediate inputs from the tripartite input-output table, where z, x, c and f are the intermediate input, total output, consumption and emission coefficient of the energy sector. $\mathbf{g}^D$, $\mathbf{g}^P$, and $\mathbf{g}^N$ are the estimated emissions based on the energy sectors of classes D, P and N. The corresponding emission ratio of each class is given by $\mathbf{w}^D = \mathbf{g}^D/(\mathbf{g}^D + \mathbf{g}^P + \mathbf{g}^N)$, $\mathbf{w}^P = \mathbf{g}^P/(\mathbf{g}^D + \mathbf{g}^P + \mathbf{g}^N)$ and $\mathbf{w}^N = \mathbf{g}^N/(\mathbf{g}^D + \mathbf{g}^P + \mathbf{g}^N)$. The actual emissions associated with each class are then obtained as $\mathbf{q}^D = \mathbf{q} \times \mathbf{w}^D$, $\mathbf{q}^P = \mathbf{q} \times \mathbf{w}^P$ and $\mathbf{q}^N = \mathbf{q} \times \mathbf{w}^N$.

3. Results

3.1. Embodied air pollutants in Chinese exports

We examine the embodied air pollutants and value added in the domestic final demand and exports in China in 2012 through the extended non-competitive input-output table that captures processing exports. The results are summarized in Table 3.

Table 3 shows that exports contributed nearly 20% (12.94 million tons) of Chinese air pollutants in 2012. Moreover, the embodied value added in exports accounted for 17.36% (9.32 trillion yuan) of the gross GDP. The embodied air pollutants in gross exports can be further divided into embodied emissions in normal and processing exports. The levels of embodied air pollutants induced by processing exports are much lower than those induced by normal exports. The embodied air pollutants in processing and normal exports account for 3.08% and 15.60% of the gross air pollutants in China, respectively.

The value of gross exports in 2012 totaled $2.05 trillion, and processing exports accounted for 42.11% of this total.[3] Table 3 shows that processing exports generated 22.81% of the value added induced by gross exports. Additionally, the embodied air pollutants in processing exports accounted for only 16.48% of the emissions induced by gross exports. Processing exports in China involve lower added values and air pollutant levels compared to normal exports for the same export level. In addition, the emissions per unit of value added for the production of normal exports is 1.5 times that for processing exports. Notably, processing exports are cleaner than normal exports.

We further investigate the emissions of each sector driven by Chinese exports from the forward perspective (Table 4) and identify the air

[3] Source: the data is obtained from Ministry of Commerce of the People's Republic of China. Available at: http://zhs.mofcom.gov.cn/article/Nocategory/201304/20130400107790.shtml.

Table 3
Embodied air pollutants (unit: million tons) and value added (unit: trillion yuan) in the Chinese domestic final demand and exports in 2012.

Item	Domestic final demand	Gross exports			Sum
		Normal exports	Processing exports	Sum	
Embodied air pollutants	56.33 (81.32%)	10.81 (15.60%)	2.13 (3.08%)	12.94 (18.68%)	69.27 (100.00%)
Embodied value added	44.36 (82.64%)	7.19 (13.40%)	2.13 (3.96%)	9.32 (17.36%)	53.68 (100.00%)

pollutant trends driven by the exports of each sector from the backward perspective (Table 5).

Table 4 shows that the top five sectors with the largest volumes of embodied air pollutants in normal and processing exports are similar. The Production and Supply of Electric Power and Heat Power (sector 96) emitted the largest volume of air pollutants to support normal (3.77 million tons) and processing exports (0.89 million tons) in China. The other key sectors with large volumes of air pollutants driven by both normal and processing exports included the Manufacturing and Casting of Steel and Iron (sector 59), Manufacturing and Casting of Nonferrous Metals and Related Alloys (sector 62) and Road Transportation (sector 105). Policy makers should attempt to reduce the pollution intensity of these sectors to reduce the air pollutants embodied in Chinese exports. Islam et al. (2016) found that the electricity sector and metal sector were the main contributors of SO_2 and NO_X in China, and the finding is consistent with emissions of each sector driven by Chinese exports from the forward perspective.

Table 5 shows that the top five sectors with the largest embodied emissions from the backward perspective are quite different from those from the forward perspective. For normal exports, Chinese trade-related air pollutants are mainly driven by the normal exports of Metal Products (sector 64, 0.68 million tons), which drove 6.27% of the gross air pollutants embodied in Chinese normal exports. For processing exports, Chinese trade-related air pollutants are mainly driven by the processing exports from the Computer sector (sector 86, 0.44 million tons), which accounted for 20.87% of the gross air pollutants embodied in Chinese processing exports. The results imply that air pollutants embodied in processing exports may correspond to a greater degree of sector concentration than that of normal exports (see Appendix E). The gross air pollutants embodied in the top five sectors account for as much as 56.20% of the gross embodied air pollutants in processing exports, and this percentage is only 26.47% for normal exports.

Table 4
Top five sectors with the largest volumes of emissions (million tons) driven by Chinese exports.

Item	Sector	Embodied emissions
Nominal exports	Production and Supply of Electric Power and Heat Power	3.77
	Manufacturing and Casting of Steel and Iron	0.95
	Road Transportation	0.62
	Basic Chemical Raw Materials	0.49
	Manufacturing and Casting of Nonferrous Metals and Alloys	0.44
Processing exports	Production and Supply of Electric Power and Heat Power	0.89
	Manufacturing and Casting of Steel and Iron	0.17
	Manufacturing and Casting of Nonferrous Metals and Alloys	0.13
	Basic Chemical Raw Materials	0.11
	Road Transportation	0.10
Gross exports	Production and Supply of Electric Power and Heat Power	4.66
	Manufacturing and Casting of Steel and Iron	1.12
	Road Transportation	0.72
	Basic Chemical Raw Materials	0.60
	Manufacturing and Casting of Nonferrous Metals and Alloys	0.57

(Notes: The classification of all sectors are shown in Table D1 of Appendix D.).

Table 5
Top five sectors with the largest volumes of emissions (unit: million tons) embodied in their own exports.

Item	Sector	Embodied emissions
Nominal exports	Metal Products	0.68
	Steel Rolled Products	0.66
	Basic Chemical Raw Materials	0.56
	Textile and Clothing	0.54
	Business Service	0.43
Processing exports	Computer	0.44
	Communication Equipment	0.26
	Stationeries, Sports Goods and Entertainment Supplies	0.23
	Ships and Related Devices	0.18
	Rubber Products	0.08
Gross exports	Metal Products	0.73
	Steel Rolled Products	0.67
	Basic Chemical Raw Materials	0.60
	Textile and Clothing	0.59
	Computer	0.45

(Notes: The classification of all sectors are shown in Table D1 of Appendix D.).

Tables 4 and 5 only show the top five sectors that contribute most to the air pollutants embodied in Chinese exports from both forward and backward perspectives. This study further adopts a Sankey diagram to show the flows of embodied air pollutants among different sectors (see Fig. 1). The largest exporter of normal exports is Production and Supply of Electric Power and Heat Power (sector 64), which emitted as much as 0.28 million tons of air pollutants to support the normal exports of Basic Chemical Raw Material (sector 41). Additionally, the Production and Supply of Electric Power and Heat Power (sector 64) emitted 0.20 million tons of air pollutants to support the processing exports from the Computer (sector 86).

Results in this section are based on the extended input-output table that captures processing exports. Previous research without accounting for the trade heterogeneity may have yielded biased results; the accounting differences will be explained in detail in section 3.2.

3.2. Comparison of embodied air pollutants under three methods

This section provides a comparison of embodied air pollutants using three methods to investigate the effects of trade heterogeneity on the estimation of embodied air pollutants in Chinese exports. Method 1 estimates embodied air pollutants in Chinese exports based on the extended tripartite input-output table that captures processing exports. Methods 2 and 3 are based on the non-competitive input-output table and competitive input-output table for China that fail to distinguish processing exports from normal exports. The competitive and non-competitive input-output tables are obtained by aggregating the extended tripartite table. The calculated embodied air pollutants in Chinese exports under the three methods are shown in Fig. 2.

Fig. 2 shows that Methods 2 and 3 overestimate the air pollutants embodied in Chinese exports. Compared with Method 1, the embodied emissions in Method 2 and Method 3 are overestimated by 12.83% (1.66 million tons) and 21.38% (2.77 million tons), respectively. This result is

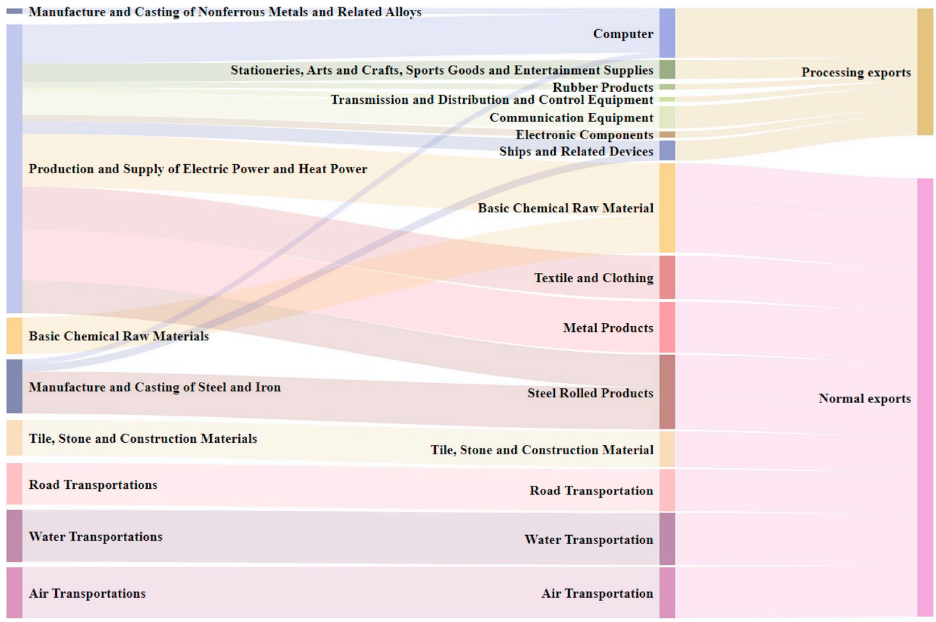

Fig. 1. Top ten transfer flows of embodied emissions in processing and normal exports in 2012.

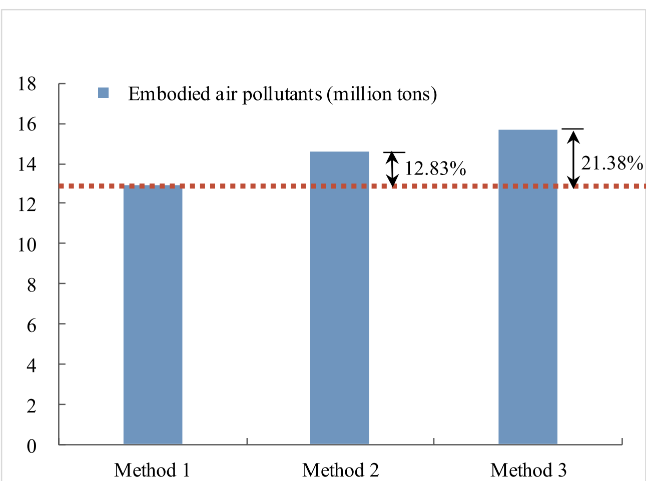

Fig. 2. Embodied air pollutants (unit: million tons) in Chinese exports under three methods.

consistent with those of similar studies that focused on carbon emissions. The findings indicate that carbon dioxide emissions induced by exports are overestimated by 15%–60% without taking trade heterogeneity into account (Dietzenbacher et al., 2012; Su and Ang, 2013; Jiang et al., 2016). Compared with Method 1, Method 2 does not distinguish between processing exports and normal exports. As noted above, processing exports are cleaner than normal exports; hence, Method 2, which does not capture processing exports, results in the overestimation of the embodied air pollutants in exports. Compared with Method 2, Method 3, which is based on the competitive input-output table, does not distinguish between domestic and imported commodities. Since the emission intensity of domestic commodities is generally larger than that of imported commodities, Method 3 overestimates the embodied air pollutants in exports compared with Method 2.

The economic activities and emissions of various sectors differ considerably along trade or supply chains. The effects of trade heterogeneity on various sectors are also different. To capture the key sectors influenced by trade heterogeneity, we combine the original 139 sectors into 29 sectors and investigate the overestimation of embodied air pollutants in these sectors. The overestimation of embodied emissions for each sector in Method 2 and Method 3 compared with those in Method 1 are illustrated in Fig. 3. The classification of the aggregated sectors is presented in Table D1 of Appendix D.

Fig. 3 shows that the sectors with high overestimations in Method 2 and Method 3 are similar, including Production and Supply of Electric Power and Steam Hot Water (POWER), Metal Smelting and Rolling Processing (METAL-SMELTING) and Chemical Industry (CHEMICAL) sectors. The overestimation in Method 3 is generally greater than that in Method 2. For instance, the air pollutants emitted by the Production and Supply of Electric Power and Steam Hot Water (POWER) sector to support Chinese exports are overestimated by 0.69 million tons (14.75%) and 1.19 million tons (25.62%) under Methods 2 and 3, respectively. The sector with the largest overestimation value is Production and Supply of Electric Power and Steam Hot Water (POWER) in both Method 2 and Method 3. The sectors with the largest ratio of overestimation in Method 2 is Paper Printing (PAPER, 19.84%) and in Method 3 is Mining of Metal Ores (METAL-MINING, 46.66%). To avoid the overestimation of the air pollutants embodied in Chinese exports, policy makers should make a clear distinction between the air pollutants emitted by these sectors to support normal and processing exports.

3.3. Unequal distribution of export-related air pollutants and value added

Table 3 in section 3.1 compares the pollution and value added contributions from the two types of exports and shows that export-related air pollutants and value added are unequally distributed between normal and processing exports. The export-related air pollutants and value added may be also unequally distributed at the sector level. A sector may emit a large volume of air pollutants to support Chinese exports but contribute to only a small portion of the value added. This section compares the distributions of export-related air pollutants and value added for the 29 aggregated sectors. Top five sectors of export-related air pollutants and value added are presented in Table 6.

As shown in Table 6, air pollutants driven by Chinese exports are mainly emitted by Production and Supply of Electric Power and Steam Hot Water. For example, Production and Supply of Electric Power and Steam Hot Water generates 34.89% of emissions driven by normal

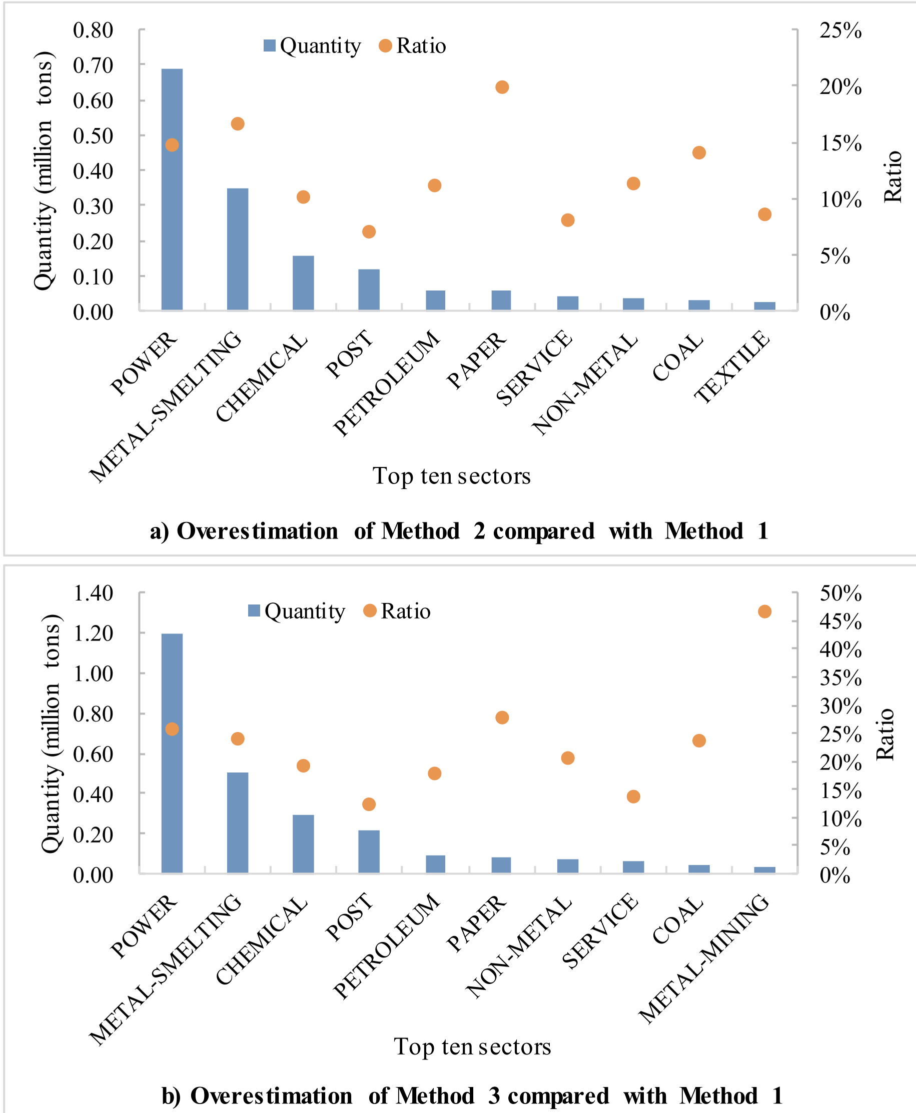

Fig. 3. The quantity (unit: million tons) and ratio of overestimation for top ten sectors in Method 2 and Method 3 compared with Method 1. (Notes: The figure shows abbreviations for sectors, and the full names of sectors are listed in Table D1 of Appendix D.).

exports and 41.78% of emissions driven by processing exports. Wholesale and Retail sector and Other Service Industry contribute more than 30% of value added embodied in normal exports. While value added embodied in processing exports are mainly driven by Manufacturing of Electronics and Communication Equipment.

There are unequal distributions of export-related air pollutants and value added at the sector level. Both the normal and processing exports from some sectors, including the Production and Supply of Electric Power and Steam Hot Water; Metal Smelting and Rolling Processing Industry; Chemical Industry; and Transportation, Warehousing, Post and Telecommunications sectors, release large quantities of air pollutants but add little value to the final product. For instance, the Production and Supply of Electric Power and Steam Hot Water (POWER) emits 34.89% of normal export-related air pollutants and accounts for only 2.88% of the normal export-related value added. In contrast, some sectors exhibit small ratios of air pollution per unit of value added. These sectors include the Other Service Industry, Wholesale and Retail sector, and Agriculture sector. For example, the Other Service Industry (SERVICE) sector contributes to 11.20% of processing export-related value added and only 3.07% of processing export-related emissions. Moreover, significant differences in embodied air pollutants and the value added embodied in normal and processing exports exist for some sectors. For instance, the Electronics and Communication Equipment sector obtains as much as 23.11% of value added embodied in China's processing exports, but the share for normal exports is only 2.39%, suggesting that this sector may play a more important role in processing exports.

4. Conclusions and policy implications

China has become the world's largest exporter, and air pollutants embodied in Chinese exports have attracted attention from both academic and practical research. Processing exports play a significant role in Chinese exports. Without taking trade heterogeneity into account, existing studies of embodied air pollutants in exports may be biased. This paper re-examines the air pollutants embodied in Chinese exports based on an extended non-competitive input-output table that distinguishes processing exports from normal exports. The main conclusions are presented below.

Processing exports are shown to be cleaner than normal exports. Processing exports generate 22.81% of the value added but only 16.48% of the emissions embodied in gross exports. Moreover, the emissions per

Table 6
Share of export-related air pollutants and value added for the top five sectors a) Top five sectors of air pollutants and value added embodied in Normal exports.

Item	Sector	Share of air pollutants	Share of value added
Air pollutants	Production and Supply of Electric Power and Steam Hot Water	34.89%	2.88%
	Metal Smelting and Rolling Processing Industry	16.21%	4.95%
	Transportation, Warehousing, Post and Telecommunications	14.07%	6.20%
	Chemical Industry	12.07%	6.91%
	Petroleum Processing and Coking Industry	3.97%	1.96%
Value added	Wholesale and Retail	0.32%	17.80%
	Other Service Industry	3.86%	15.45%
	Agriculture	0.88%	7.21%
	Chemical Industry	12.07%	6.91%
	Transportation, Warehousing, Post and Telecommunications	14.07%	6.20%

b) Top five sectors of air pollutants and value added embodied in processing exports

Item	Sector	Share of air pollutants	Share of value added
Air pollutants	Production and Supply of Electric Power and Steam Hot Water	41.78%	2.31%
	Metal Smelting and Rolling Processing Industry	16.59%	3.85%
	Chemical Industry	11.12%	7.37%
	Transportation, Warehousing, Post and Telecommunications	8.29%	2.82%
	Petroleum Processing and Coking Industry	4.31%	1.17%
Value added	Manufacturing of Electronics and Communication Equipment	0.55%	23.11%
	Other Service Industry	3.07%	11.20%
	Wholesale and Retail	0.21%	7.71%
	Chemical Industry	11.12%	7.37%
	Manufacturing of Paper Printing and Stationery	3.08%	5.59%

unit of value added for the production of normal exports is 1.5 times that of processing exports. China has implemented strict environmental regulations on processing exports. In the future, trade-related environmental regulations should also be directed to normal exports that contribute a larger share of embodied air pollutants in Chinese exports. Air pollutants are mainly released by the Production and Supply of Electric Power and Heat Power (sector 96) and Manufacturing and Casting of Steel and Iron (sector 59) sectors to yield normal exports from the Metal Products (sector 64) and Steel Rolled Products (sector 60) sectors and processing exports from the Computer (sector 86), Communication Equipment (sector 87) sectors.

The air pollutants embodied in Chinese exports would be overestimated without considering trade heterogeneity. Compared with the extended non-competitive input-output table that captures processing trade, the embodied air pollutants based on the non-competitive input-output and competitive input-output tables would be overestimated by 12.83% (1660 kt) and 21.38% (2766 kt), respectively. The embodied air pollutants in the exports from the Electric Power and Steam Hot Water (POWER), Metal Smelting and Rolling Processing (METAL-SMELTING) and Chemical Industry (CHEMICAL) sectors were significantly overestimated. Therefore, trade heterogeneity has a considerable impact on the estimation of embodied air pollutants in these sectors. Policy makers should strongly consider the distinction between the normal and processing exports from the Computer and Communication Equipment sectors, of which the processing exports account for the largest portion of air pollutants.

Trade-related air pollutants and value added are unequally distributed among different sectors. The service sectors, such as Wholesale and Retail (RETAIL), account for relatively large shares of value added embodied in Chinese exports but emit less pollutants that are driven by exports. Conversely, industrial sectors, such as Production and Supply of Electric Power and Steam Hot Water (POWER), generate large volumes of pollutants to support Chinese exports but account for less of the value added embodied in exports. These sectors should be strictly controlled and prioritized to improve the emission efficiency.

In order to avoid developed countries outsourcing pollution-intensive production stages to China, the Chinese government has restricted processing exports of commodities such as metal raw materials, coal and slag.[4] Production of these commodities are mainly from the chemical industry and metal sectors. Are government's restrictions on the sectors effective? Assuming that processing exports of Basic Chemical Raw Materials (sector 41), Manufacturing and Casting of Steel and Iron (sector 59) are restricted by 10%, we calculate changes in emissions to investigate the effects of these restrictive measures. The results show that restrictions on the two sectors can only reduce emissions by 0.28%, implying that present restrictive policies have very limited capacity to reduce embodied emissions in processing exports. Traditional restrictions only cover sectors with large emissions from the forward perspective. The main sectors that drive large emissions to support their own processing exports are not included. From the backward perspective, we examine changes in emissions after restricting 10% of processing exports of Computer (sector 86) and Communication Equipment (sector 87). Results show that restricting 10% of processing exports of Computer (sector 86) and Communication Equipment (sector 87) would decrease emissions by 6.24%. Therefore, current restrictions on specific sectors from the forward perspective may contribute little to emission reduction. Policy makers should pay more attention to sectors that drive large emissions (such as Computer and Communication Equipment) when restricting processing exports in future. It should be noted that above policy implications are given based on reduction of emissions without considering impacts on economy. Sectors that drive large emissions usually could produce more value added, so restrictions on these sectors may have a side effect on economic benefits. In addition, our policy suggestions are given based on results in 2012 due to data limited. Chinese exports have declined in the past few years, and the effect of exports on various sectors has varied. If data is available, the temporal variation of embodied air pollutants could be estimated to conduct more comprehensive analysis in future research.

One uncertainty of input-output model is the aggregation level of sectors. we aggregate all data in the model from 139 sectors to 29 sectors, 7 sectors and 3 sectors respectively to evaluate effects of methodology uncertainty on our results. Meanwhile, according to Zhang et al. (2015), we increase emissions of each sector with 5%, 10% and 20% respectively to evaluate effects of emission data uncertainty on our results. According to results of sensitivity analysis, aggregation level of sectors and emission data uncertainty may have a little impact on our

[4] Source: http://www.mofcom.gov.cn/article/ae/ai/200611/20061103684781.shtml.

results but will not affect the conclusion (see Appendix F). In addition, this study has several limitations. For instance, we only chose SO_2, NO_X and soot, which are the main precursors of $PM_{2.5}$, to evaluate the effects of trade heterogeneity on the embodied air pollutants induced by exports. Since $PM_{2.5}$ is the chief air pollutant in China, it would be more comprehensive if $PM_{2.5}$ emission data could be obtained and analyzed. Secondly, this study is a static analysis, and Chinese exports have changed significantly over time. As mentioned in policy implications, future studies could evaluate the temporal variations of air pollution by comparing the embodied emissions in different years. Moreover, the methodology developed in this study could be applied to other indicators, including water, carbon dioxide and energy.

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Appendix A. Supplementary data

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