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Spatial production fragmentation and $PM_{2.5}$ related emissions transfer through three different trade patterns within China

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ABSTRACT

$PM_{2.5}$ is the major component of severe haze pollution in China. Some studies have reported that large scale of $PM_{2.5}$ related emissions are derived from trade activities. However, little research has been carried out about the assessment of emissions related to different trade patterns, especially the trade related to spatial production fragmentation. Based on multi-regional input–output model, this study analyzed the transfer of $PM_{2.5}$ related emissions through three different trade patterns in China, i.e. the trade of final products (T_f), the trade of intermediate products for the last stage of production (T_i) and the trade for the domestic and global value chain (T_v). Results showed that the trade of intermediate products from inland regions to coastal regions in China contributed to additional $PM_{2.5}$ related emissions thereby being in line with the pollution haven hypothesis, i.e. a shifting of pollution-intensive industry from countries with stringent environmental regulations to countries with weaker environmental regulations. In contrast, the trade of final products from coastal regions to inland regions generated savings in $PM_{2.5}$ related emissions. The largest share of embodied air pollutants is from T_v trade pattern, which means spatial production fragmentation has become a key factor to affect embodied emissions flows.

1. Introduction

In recent decades, economic activities have coupled with serious environmental problems in China (Jiang et al., 2017). The $PM_{2.5}$ is the major component of haze and regional air pollution has led to extensive global concern. Recently, studies on $PM_{2.5}$ related emissions embodied in economic and trade activities have attracted growing attention. For example, from the international perspective, the research from Zhang et al. (2017a) revealed that the health impacts of $PM_{2.5}$ pollution associated with international trade were greater than those associated with long-distance atmospheric pollutant transport. For the provincial trade in China, emissions embodied in intermediate products made up a large portion of total emissions embodied in interprovincial trade in 2007 (Zhao et al., 2015); the central and western provinces were the main exporters of intermediate products while the eastern coastal provinces and Beijing were the main importers due to final consumption and international export-related activities (Wu et al., 2017).

Although previous studies revealed the relationship between $PM_{2.5}$ emissions and trade activities, little attention was paid to comparing emissions embodied in the different trade patterns. With the development of industrial segmentation, production processes have become increasingly spatially fragmented (Dietzenbacher et al., 2012). In China, spatial production fragmentation (the location of different stages of the production chain in different regions) has led to different regions specializing in different production stages. These regions also connect with each other and other countries through various trade linkages thereby making it imperative to examine the environmental effects of different trade patterns from the perspective of spatial production fragmentation.

To better research the trade related $PM_{2.5}$ emissions, this study analyzed the $PM_{2.5}$ related emissions embodied in three different

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trade patterns, i.e. the trade of final products (T_f), the trade of intermediate products for the last stage of production (T_i) and the trade for the domestic and global value chain (T_v). These three trade patterns are divided by the border-crossing frequency of traded products. A production chain may cross many regions due to production fragmentation. This will affect the embodied air pollutants emissions embodied in the final products.

The study applied the multi-regional input-output (MRIO) analysis framework to trace $PM_{2.5}$ related emissions (i.e. primary $PM_{2.5}$ and it's precursors: SO_2, NO_x and NMVOC) in China's domestic trade. It is a common approach that the balance of embodied emissions (*BEE*) and the balance of avoided emissions (*BAE*) are employed to study the relationship between environment and trade in the research field of economics (Zhang et al., 2017b). In this paper, $PM_{2.5}$ related emissions embodied in three trade patterns from the perspectives of *BEE* and *BAE* were examined by the similar method. Based on multi-regional input–output analysis framework, this study explained the environmental effects of different trade patterns within China. The results will be useful to further understand the regional responsibility for pollution so that corresponding regional trade policy can be developed. The overall organization of this study is summarized as below.

First, this study decomposed a region's production-based gross $PM_{2.5}$ related emissions induced by export into three different trade patterns. Second, the top 10 inter-regional *BEE* flows of $PM_{2.5}$ related emissions across seven regions due to the different trade patterns were analyzed. Third, the spatial Logarithmic Mean Divisia Index (LMDI) method was applied to interpret the *BEE* flows and while the importance of intensity effect. Fourth, the effects of trade on regional and national emissions further analyzed by *BEE* and *BAE*. *BAE* was used to test the PHH in this section. Finally, the main conclusions of this study were summarized and policy implications were provided.

2. Data sources and methodology

2.1. Data source and processing

The $PM_{2.5}$ related emissions provincial data of primary $PM_{2.5}$, SO_2, NO_x and NMVOC in 2010 were derived from the multi-resolution emission inventory for China (MEIC) compiled by Tsinghua University. Data of 30 provinces retrieved from the MEIC were aggregated into seven regions (see Appendix A Table A.1). MEIC is a unit/technology-based, bottom-up air pollutant emission inventory. It covers 10 pollutants (SO_2, NO_x, $PM_{2.5}$, NH_3, CO, BC, OC, VOC, PM_{10}, and PM coarse) and CO_2 for 700 anthropogenic emission sources. Detailed inventory methodology is available on the MEIC web (www.meicmodel.org/methodology.html, accessed 10 September 2017) (Zhao et al., 2016).

The 30-provinces MRIO table in 2010 was retrieved from the Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences (Liu et al., 2014). All 30 provinces were also aggregated into seven regions consistent with emissions data.

2.2. Methodology

2.2.1. The decomposition of a region's gross pollutant emissions

The input-output analysis on the environmental effects of trade patterns related to production fragmentation can be divided into two types. The first type adopts single region input-output (SRIO) analysis framework and differentiates the input structures of processing and nominal exports (Su et al., 2013). The second type adopts multi-regional input-output (MRIO) analysis framework and traces carbon emissions in domestic (Liu and Wang, 2015) or global (Davis and Caldeira, 2010) value chains by sources, destinations and transfer channels of emissions. This study also adopts a MRIO analysis framework.

This section explains the methodology and is based on a country composed of *G* regions and *N* sectors. These regions are connected through the inter-regional trade of intermediate and final products, and each region is connected with the world economy through inter-regional imports and exports. The economic linkage among these regions is presented as a multi-regional input-output table, as shown in Table A.2. The further description for MRIO analysis was shown in Appendix A. Table A.3 presents the meaning of different variables in the followed equations.

The pollutant emission intensity of the sector *i* of region *s* is defined as $f_i^s = e_i^s / x_i^s$, where e_i^s represents the pollutant emissions of the sector *i* of regions. F^s is a diagonal matrix made up of f_i^s. The gross pollutant emissions of region *s* is

$$\begin{aligned} E^s &= F^s X^s \\ &= F^s L^{ss} Y^{ss} + F^s L^{ss} EX^s + F^s L^{ss} \sum_{s \neq r}^{G} T\_f^{sr} + F^s L^{ss} \sum_{s \neq r}^{G} T\_i^{sr} \\ &\quad + F^s L^{ss} \sum_{s \neq r}^{G} T\_v^{sr} \end{aligned} \tag{1}$$

The detailed derivation process for equation (1) was shown in Appendix A section from equation (A.1) to equation (A.5).

The gross pollutant emissions of region *s* are decomposed into five terms. The first term represents emissions induced by economic activity within region *s* that has no relation with the inter-regional or international production fragmentation. The other four terms represent the emissions induced by different trade patterns. The decomposition is presented in Fig. 1.

2.2.2. The balance of embodied emissions (BEE)

Then the domestic emissions embodied in exports from region *s* to region *r* is

$$EEX^{sr} = F^s L^{ss} T^{sr} = F^s L^{ss} T\_f^{sr} + F^s L^{ss} T\_i^{sr} + F^s L^{ss} T\_v^{sr} \tag{2}$$

Equation (2) decomposes the emissions embodied in gross exports from region *s* to region *r* into three terms by the trade pattern, the traditional trade of final products, the traditional trade of intermediate products, the domestic and the global value chain related trade. Then the balance of embodied emissions can be revealed as:

$$\begin{aligned} BEE^{sr} &= EEX^{sr} - EEX^{rs} \\ &= \underbrace{\left(F^s L^{ss} T\_f^{sr} - F^r L^{rr} T\_f^{rs}\right)}_{(3-1)} + \underbrace{\left(F^s L^{ss} T\_i^{sr} - F^r L^{rr} T\_i^{rs}\right)}_{(3-2)} \\ &\quad + \underbrace{\left(F^s L^{ss} T\_v^{sr} - F^r L^{rr} T\_v^{rs}\right)}_{(3-3)} \end{aligned} \tag{3}$$

Term (3–1) represents the balance of emissions embodied in traditional trade of final products; term (3–2) represents the balance of emissions embodied in traditional trade of intermediate products; term (3-3) represents the balance of emissions embodied in global and domestic value chain related trade.$BEE^{sr} > 0$ means the bilateral production fragmentation promotes the pollutant emissions of region *s* ; otherwise, the bilateral production fragmentation contributes to a decrease in the pollutant emissions of region *s*. The effects of position in the national production fragmentation on pollutant emissions of region *s* is

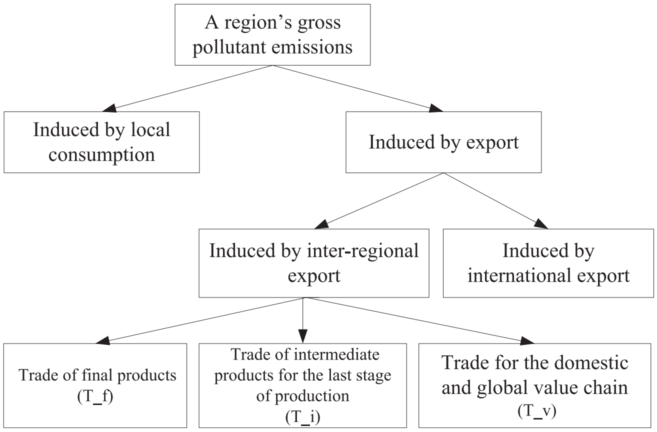

Fig. 1. The decomposition of a region's gross pollutant emissions.

$$BEE^s = \sum_{r \neq s}^{G} EEX^{sr} - \sum_{r \neq s}^{G} EEX^{rs} \tag{4}$$

$BEE^s > 0$ means the position in the national production fragmentation contributes to an increase in the pollutant emissions of region s. $BEE^s < 0$ means the position in the national production fragmentation promotes a decrease in the pollutant emissions of region s. Nevertheless, it is impossible to use *BEE* to know the influence of inter-regional trade on national emissions because the aggregation of *BEE* for all regions is always zero ($\sum_s^G BEE^s = 0$).

2.2.3. Spatial LMDI model for decomposition BEE

Although trade pattern and flows affect the regional *BEE* seriously, the disparity of emission intensity is also a major influencing factor. The emission intensity represents the air pollution control technology development. Decomposition analysis has been widely used to quantify the driving forces of changes of an aggregate indicator in energy, emissions, and other social-economic areas over time, which is called temporal decomposition analysis. The original application was for decomposition of energy-related CO_2 emissions and quantifying the contribution of each factor such as scale effect, structure effect, intensity effect, etc. (Wang et al., 2005). Recently, the spatial decomposition analysis was put forward to study the variations of an aggregate indicator (such as total energy or emissions, or emission intensity) between regions (Ang et al., 2017).

Based on previous research of decomposition analysis, in order to give quantified interpretation, Logarithmic Mean Divisia Index method (LMDI) was applied to analyze the impact of trade on pollution from the perspectives of scale effect and intensity effect. Both the scale effect and the intensity effect impact those emissions embodied in trade. These two contributing factors for regional *BEE* were analyzed. In general, the LMDI method is employed to analyze changes between year t and t+1. Year t and t+1 were replaced with region r and$s$, then the LMDI can also be employed to examine the spatial disparity.

In this paper, the gross emission intensity of region s can be expressed as:

$$I^s = F^s L^{ss} \tag{5}$$

Then, according to Equation (2), EEX^{sr} can be showed as:

$$EEX^{sr} = I^s T^{sr} \tag{6}$$

According to LMDI, Equation (3) can also be expressed as:

$$BEE^{sr} = EEX^{sr} - EEX^{rs} = I^s T^{sr} - I^r T^{rs} = \Delta I(s,r) + \Delta T(s,r) \tag{7}$$

where: $\Delta I(s,r)$ represents intensity effect associated with disparity of emission intensity between region r and regions; $\Delta T(s,r)$ represents scale effect associated with trade scale from $s$to$r$.

$$\Delta I(s,r) = \frac{EEX^{sr} - EEX^{rs}}{\ln EEX^{sr} - \ln EEX^{rs}} \times \ln(I^{sr}/I^{rs}) \tag{8}$$

$$\Delta T(s,r) = \frac{EEX^{sr} - EEX^{rs}}{\ln EEX^{sr} - \ln EEX^{rs}} \times \ln(T^{sr}/T^{rs}) \tag{9}$$

Contribution of each factor can be expressed as:

$$\textit{Contribution of intensity effect} = \frac{\Delta I(s,r)}{BEE^{sr}} = \frac{\ln(I^{sr}/I^{rs})}{\ln EEX^{sr} - \ln EEX^{rs}} \tag{10}$$

$$\textit{Contribution of scale effect} = \frac{\Delta T(s,r)}{BEE^{sr}} = \frac{\ln(T^{sr}/T^{rs})}{\ln EEX^{sr} - \ln EEX^{rs}} \tag{11}$$

2.2.4. The balance of avoided emissions (BAE)

The effects of production fragmentation on the national emissions are evaluated by the difference between emissions embodied in exports and emissions avoided by imports (balance of avoided emissions, *BAE*) (López et al., 2013). It is a common approach to employ the balance of avoided emissions (*BAE*) to test "Pollution Haven Hypothesis" (PHH) in the literature (López et al., 2018; Zhang et al., 2014). The major objective of this study is to explore the environmental effects of trade activities within China. The PHH is at the center of the trade and environment debate since it makes a direct link between differences across countries in their environmental regulation and trade flows (Taylor, 2005). The emissions avoided by imports of region$s$from region$r$is

$$EAI^{sr} = F^s L^{ss} T^{rs} = F^s L^{ss} T\_f^{rs} + F^s L^{ss} T\_i^{rs} + F^s L^{ss} T\_d^{rs} + F^s L^{ss} T\_g^{rs} \tag{12}$$

Equation (12) reflects the emission of region$s$avoided by imports from region r through different trade patterns. The balance of avoided emissions (*BAE*) is:

$$\begin{aligned} BAE^{sr} &= (EEX^{sr} - EAI^{sr}) + (EEX^{rs} - EAI^{rs}) \\ &= \underbrace{\underbrace{(F^s L^{ss} - F^r L^{rr}) T\_f^{sr}}_{(13-1-1)} + \underbrace{(F^s L^{ss} - F^r L^{rr}) T\_i^{sr}}_{(13-1-2)} + \underbrace{(F^s L^{ss} - F^r L^{rr}) T\_v^{sr}}_{(13-1-3)}}_{(13-1)} \\ &\quad \underbrace{+ \underbrace{(F^r L^{rr} - F^s L^{ss}) T\_f^{rs}}_{(13-2-1)} + \underbrace{(F^r L^{rr} - F^s L^{ss}) T\_i^{rs}}_{(13-2-2)} + \underbrace{(F^r L^{rr} - F^s L^{ss}) T\_v^{rs}}_{(13-2-3)}}_{(13-2)} \end{aligned} \tag{13}$$

Term (13–1) explains the PHH from the perspectives of production structure and pollutant intensity of the exports from region$s$to region$r$, which can be further divided into three trade patterns. Term (13–2) explains the PHH from the perspectives of production structure and pollutant intensity of the imports of region s from region r, which can also be further divided into three trade patterns. According to the modified calculation approach (Zhang et al., 2014), the *BAE* is represented by:

$$BAE^{s}=\left(\sum_{r\neq s}^{G}BAE^{sr}+\sum_{r\neq s}^{G}BAE^{rs}\right)\Big/2 \tag{14}$$

The expression of gross balance of avoided emissions is presented as below.

$$BAE=\sum_{s}^{G}\sum_{r\neq s}^{G}BAE^{sr} \tag{15}$$

A positive *BAE* confirms the pollution haven hypothesis holds, which means that the trade contributes to an increase in gross emissions. In contrast, a negative *BAE* means the trade contributes to a decrease in gross emissions.

Four quadrant diagram was applied to compare BEE and BAE for seven regions. Then, the total BAE of four air pollutants for three trade patterns were calculated to reveal environmental effects of different trade patterns.

3. Results and analysis

3.1. Decomposition of a region's production-based gross $PM_{2.5}$ related emissions embodied in export

According to equation (1), a region's production-based gross $PM_{2.5}$ related emissions induced by export can be divided into the emissions induced by different trade patterns (see Fig. 2). As shown in Fig. 2, the proportions of the different trade patterns for the four air pollutants emissions were similar. Overall, a region's $PM_{2.5}$ related embodied emissions in domestic inter-regional export accounted for a larger proportion (above 50%) than that induced by international export in China. Only for southeast coast region,

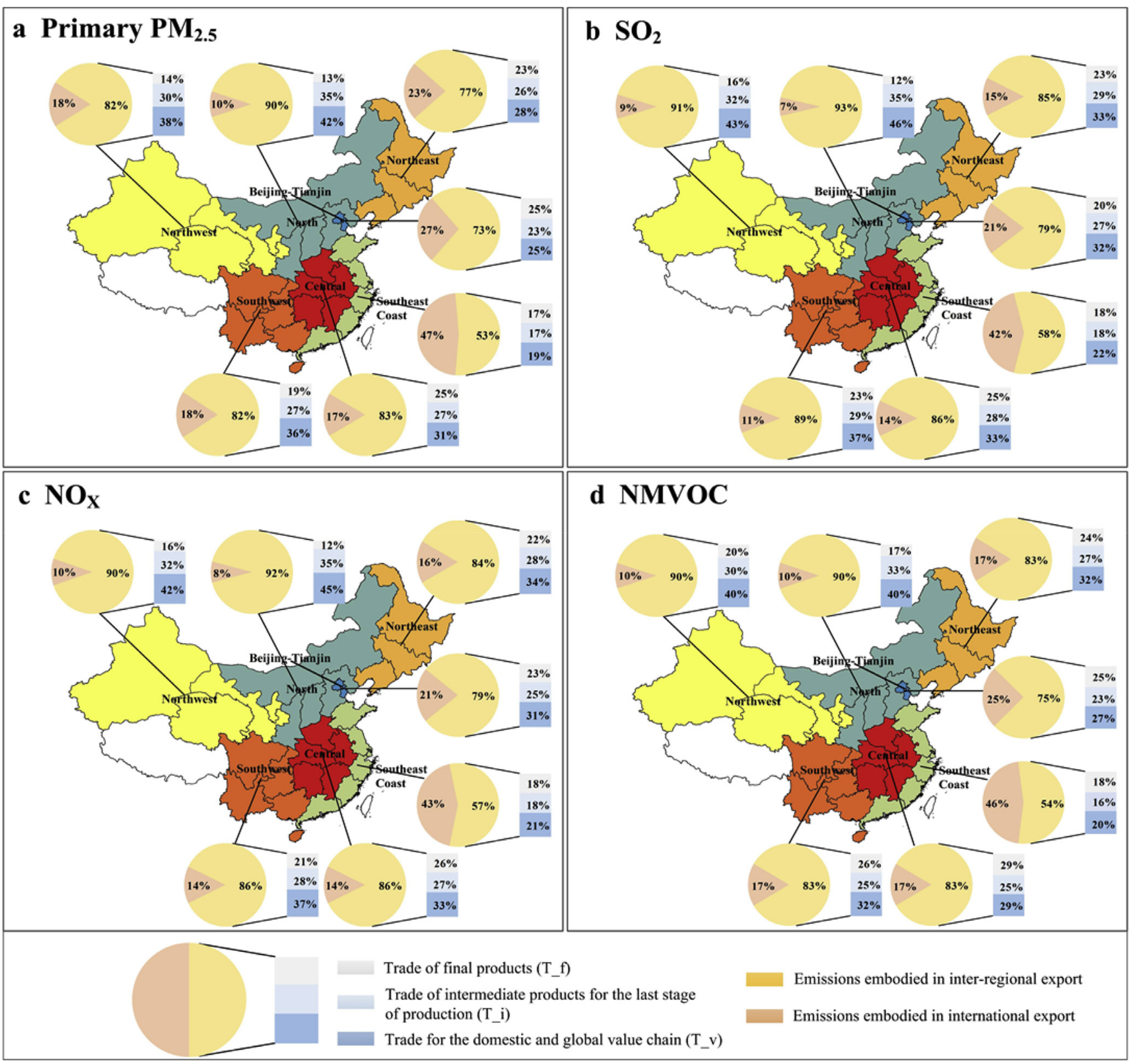

Fig. 2. Decomposition of air pollutants emissions among the seven regions in 2010, a-d. Detailed data for decomposition see Appendix B Table B.1. Tibet, Hong Kong, Macau, and Taiwan are excluded from this study, these regions are colored in white.

international export accounted for a relatively large proportion compared to other regions, above 40%. Contributions of inter-regional export and international export varied in every region because of their regional attributes. For example, primary $PM_{2.5}$ was selected to demonstrate the contribution. In north China, the emissions embodied in domestic inter-regional export accounted for the largest share, approximately 90%, and emissions embodied in international export only accounted for 10%; while in southeast coast, the emissions induced by inter-regional export and international export accounted for approximately 53% and 47%, respectively. Most of the inland areas emissions depended mainly on their inter-regional export, such as central (83%), southwest (82%), northwest (82%), northeast (77%) and Beijing-Tianjin (73%).

In domestic inter-regional export (bar graph in Fig. 2) of China, the T_v trade pattern had the largest share of domestic inter-regional exports, ranging from 19% to 46% across seven regions. In contrast, T_f trade pattern had the smallest share with a range of 12%–29%. T_i trade pattern accounted for 16%–35%, which was between that of T_v and T_f. The T_v trade pattern is the trade for domestic and global value chain, which represents the degree of spatial production fragmentation in economic system. The largest share of embodied air pollutants is from T_v trade pattern, which means spatial production fragmentation has become a key factor to affect embodied emissions flows.

The following section provides a more detailed discussion on the emissions flows embodied in the three trade patterns of domestic trade.

3.2. Distribution of $PM_{2.5}$ related BEE flows according to trade patterns

Fig. 3 presents the top 10 inter-regional *BEE* flows of primary $PM_{2.5}$ across the seven regions due to the different trade patterns. The similar *BEE* flows of SO_2, NO_x and NMVOC see Appendix C Fig. C.1, Fig. C.2 and C.3, respectively.

(1) The total *BEE* flows (Fig. 3 and Fig. C.1–C.3 T_total)

For the total domestic inter-regional trade, the spatial characteristics of the balance of embodied emissions (*BEE*) flows were similar across all four pollutants. As shown in Fig. 3 and Fig. C.1–C.3, Beijing-Tianjin and the southeast coast were the two major importing regions in terms of $PM_{2.5}$ related emissions, mainly from the north, central and southwest regions. In contrast, north China

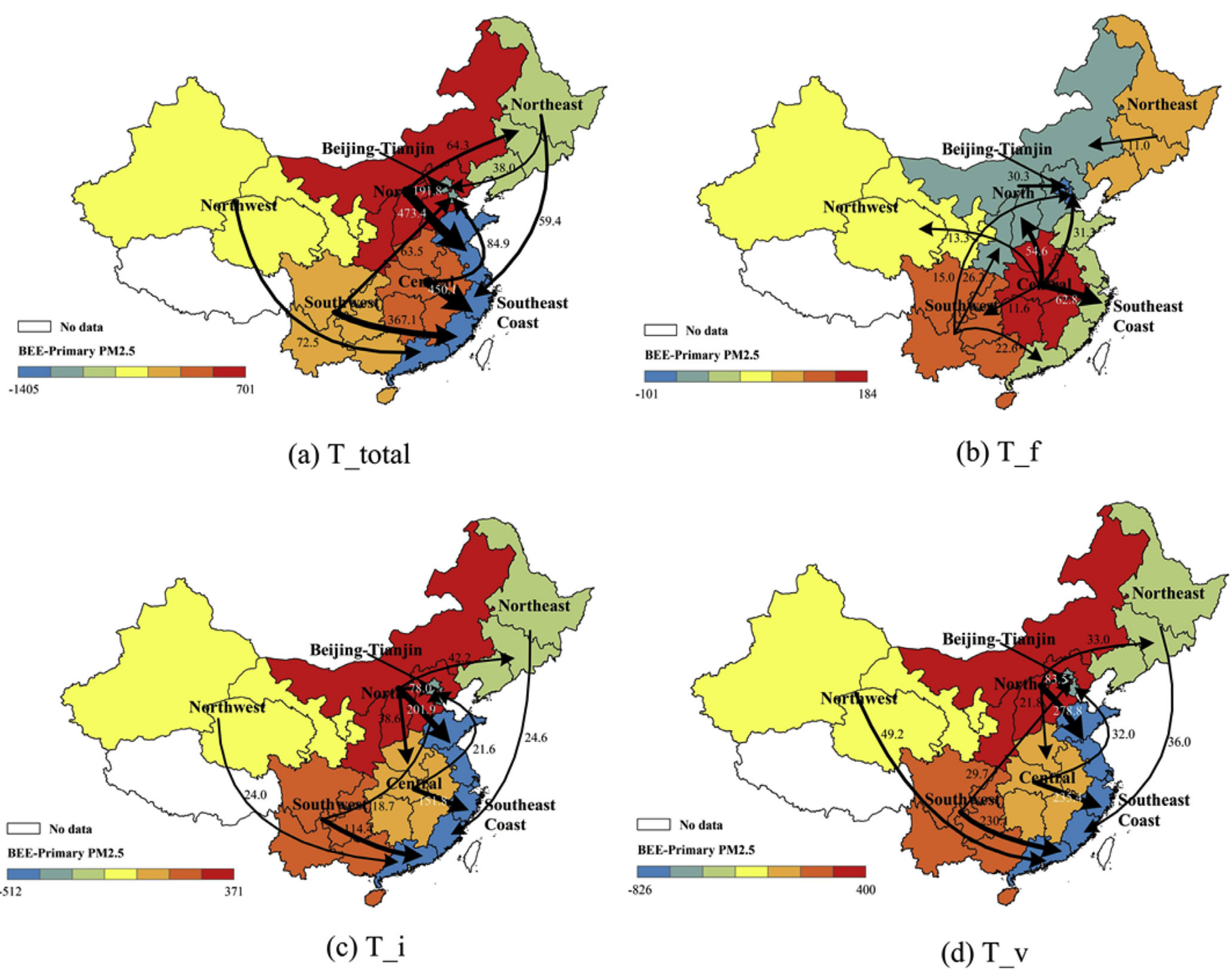

Fig. 3. The top 10 inter-regional primary $PM_{2.5}$ *BEE* flows of three trade patterns among seven regions in 2010 (unit of flows: kt), a-d. Corresponding data information see Table C.1. T_total represents the sum of the three trade patterns, i.e. T_f + T_i + T_v; the shading in each region indicates the *BEE* of air pollutants; the thickness of the black arrow indicates the inter-regional *BEE* flows.

was the region providing the highest net output of $PM_{2.5}$ related emissions, followed by the central and southwest regions. The north of China not only drove $PM_{2.5}$ related emissions to Beijing-Tianjin and the southeast coast regions, but also exported a large quantity of emissions to the northeast and central regions.

The largest domestic net $PM_{2.5}$ related emissions flows of the four air pollutants were all from the north to the southeast coast (SO_2 1275.7 kt, NO_x 1043.3 kt, primary $PM_{2.5}$ 473.4 kt and NMVOC 347.5 kt, respectively). Similarly, the second largest *BEE* flows were all from the central to the southeast coast (SO_2 931.0 kt, NO_x 780.6 kt, primary $PM_{2.5}$ 450.1 kt and NMVOC 317.6 kt, respectively).

(2) *BEE* flows of final products trade (Fig. 3 and Fig. C.1–C.3 T_f)

For the final products trade, the north of China was a large importer of all four air pollutants. The central region was the largest net exporter, with large quantities of emissions outsourced to other regions. The biggest *BEE* flows in terms of primary $PM_{2.5}$ and SO_2 were from central to the southeast coast (primary $PM_{2.5}$ 62.8 kt and SO_2 105.0 kt). The *BEE* flow from central to north was the second biggest with 54.6 kt and 86.1 kt, respectively. It is worth noting that the southeast coast was not only a major importer from the central region (77.1 kt of NO_x) but also a major exporter to the north region (83.9 kt of NMVOC).

(3) BEE flows of intermediate products trade (Fig. 3 and Fig. C.1–C.3 T_i, T_v)

For the intermediate products trade (T_i and T_v), the directions of BEE flows were almost identical across all four air pollutants. The major sources of BEE flows were from the north, central and southwest to southeast coast and Beijing-Tianjin regions, which were similar to those of the total domestic inter-regional trade (T_total).

It is worth noting that the direction of BEE flows in a certain region might vary depending on trade patterns. For example, the north region was a net emissions exporter for the T_i and T_v trade pattern; however, it was an importer for the T_f trade pattern.

3.3. *Interpretation of $PM_{2.5}$ related BEE flows*

It is clear that most *BEE* flows had the same direction as the trade flows, i.e. emissions surplus and trade surplus. However, some *BEE* flows exhibited opposite directions from trade flows, i.e. emission surplus and trade deficit. This phenomenon cannot be explained by trade flows and the spatial Logarithmic Mean Divisia Index (LMDI) method was applied in this paper to interpret the *BEE* flows. The intensity effect and the scale effect of three trade patterns on four air pollutants emissions were decomposed. Using the primary $PM_{2.5}$ to examine how the scale effect and the intensity effect drove the *BEE* flows, the top 10 regional *BEE* of three trade patterns were classified into two categories i.e.:

(1) The contribution of intensity effect was greater than the contribution of scale effect.

Most emission flows were found to belong to this category. Despite the $PM_{2.5}$ related emissions embodied in trade flows, the gap between the emission intensity of different regions facilitated the *BEE* flows. According to the direction of scale effect, this category was classified into two sub-categories as described below.

(a) Sub-category with positive contribution of scale effect (orange in Table 1)

Most emission flows embodied in the trade of intermediate products (T_i and T_v) belonged to this sub-category. The intensity effect and scale effect had the same directions. This suggests that regional diversity of emissions intensity caused greater additional emissions. For instance, the primary $PM_{2.5}$ emission intensity of the north regions was almost 8 times that of the southeast coast regions. Compared with the southeast coastal region, the clean technology and management level related to air pollutants emissions was lower in the north of China. However, the north of China was the major supplier of intermediate products to the southeast coast region, which could lead to additional emissions.

(b) Sub-category with negative contribution of scale effect (blue in Table 1)

This sub-category only existed in the trade pattern of final products. The intensity effect and scale effect had opposite directions i.e. the scale effect was negative, yet the intensity effect was positive. The intensity effect had the same direction as the emissions flow. Moreover, the absolute value of the intensity effect significantly exceeded that of the scale effect. Hence, the intensity effect dominated the emissions flow. For example, the final products were mainly produced on the southeast coast, and exported to the other regions of China. The proportion of final products exported from the southeast coast accounted for 38% with the north and central regions as the two major destinations. However, the *BEE* flows went in the opposite direction i.e. from central to the southeast coast. Hence, the intensity effect was mainly responsible for the *BEE* of the final products from the central region to the southeast coast region.

(2) The contribution of scale effect was greater than the contribution of intensity effect (green in Table 1).

This category included the trade of both final products and intermediate products. As for the trade of final products, the scale effect was the main driver for *BEE* flows from the central region to the north, northwest and southwest regions. In contrast, the effect of emission intensity was relatively smaller. As for the trade of intermediate products, the *BEE* flows from the north region to the central and northeast regions were mainly driven by the scale effect.

In short, the regional difference of emission intensity played a more important role than variations of the trade volume across regions in driving emissions embodied in the domestic trade of China. It was worth noting that the scale effect was also significant. There were also many regions where the scale effect was greater than the intensity effect, such as the green and blue in Table 1. Furthermore, due to the production fragmentation, most inland regions in China provide intermediate products to the southeast coast region. In contrast, the southeast coast region was the net exporter for final products. If only the scale effect exists, the *BEE* flows derived from the trade of final products should originate from the southeast coast region and flow to the inland regions, and the *BEE* flows derived from the trade of intermediate products should flow in the opposite direction. However, the emission's intensity effect exceeded the scale effect in most inter-regional trade patterns. This has resulted in most *BEE* flows originating from inland regions flowing to the coastal regions in China.

3.4. *Environmental effects of different trade patterns by the balance of embodied emissions (BEE) and avoided emissions (BAE)*

Primary $PM_{2.5}$ was also used as an example to compare the environmental effects of each region's trade linkages with other

Table 1
Contribution of scale effect and intensity effect of primary $PM_{2.5}$ in different trade patterns.

T_f					T_i					T_v				
Start	End	$\Delta T(s,r)$ / BEE^{sr}	$\Delta I(s,r)$ / BEE^{sr}	T^{sr} -T^{rs} (billion yuan)	Start	End	$\Delta T(s,r)$ / BEE^{sr}	$\Delta I(s,r)$ / BEE^{sr}	T^{sr} -T^{rs} (billion yuan)	Start	End	$\Delta T(s,r)$ / BEE^{sr}	$\Delta I(s,r)$ / BEE^{sr}	T^{sr} -T^{rs} (billion yuan)
central (63%)	north (20%)	0.82	0.18	191	north (50%)	central (5%)	1.03	-0.03	105	north (40%)	central (2%)	1.20	-0.20	66
	northwest (5%)	0.89	0.11	48		northeast (6%)	0.65	0.35	80		northeast (3%)	0.47	0.53	44
	southwest (4%)	1.86	-0.86	98		southeast coast (28%)	0.45	0.55	328		southeast coast (27%)	0.48	0.52	486
	southeast coast (23%)	-0.21	1.21	-99		Beijing-Tianjin (11%)	0.46	0.54	132		Beijing-Tianjin (8%)	0.41	0.59	126
	Beijing-Tianjin (11%)	-0.09	1.09	-19	central (24%)	southeast coast (21%)	0.23	0.77	148	central (26%)	southeast coast (23%)	0.43	0.57	436
southwest (22%)	north (9%)	0.75	0.25	87		Beijing-Tianjin (3%)	0.05	0.95	5		Beijing-Tianjin (3%)	0.17	0.83	23
	southeast coast (8%)	-1.43	2.43	-272	southwest (19%)	southeast coast (16%)	0.02	0.98	9	southwest (25%)	southeast coast (22%)	0.35	0.65	283
	Beijing-Tianjin (5%)	-0.64	1.64	-79		Beijing-Tianjin (3%)	0.04	0.96	3		Beijing-Tianjin (3%)	0.27	0.73	28
north (11%)	Beijing-Tianjin (11%)	-0.25	1.25	-51	northeast (3%)	southeast coast (3%)	0.23	0.77	32	northeast (4%)	southeast coast (4%)	0.49	0.51	94
northeast (4%)	north (4%)	1.75	-0.75	93	northwest (4%)	southeast coast (4%)	0.06	0.94	6	northwest (5%)	southeast coast (5%)	0.47	0.53	92

Note: The percentage in the table represents the ratio of each *BEE* flow to the sum of top 10 *BEE* flows. The similar contribution of effect analysis of SO_2, NO_x and NMVOC see Appendix D Table D.1, Table D.2 and Table D.3, respectively.

regions from the perspectives of the *BEE* and *BAE* (Fig. 4). The *BEE* showed the impact of inter-regional trade on each region's local direct emissions, and the *BAE* showed the effects of inter-regional trade on national emissions. All seven regions were attributed to four quadrants under different trade patterns in Fig. 4.

Fig. 4a reflected the environmental effects of the total trade flows. The north, central, and southwest regions were located in the first quadrant, with a positive *BEE* and a positive *BAE*. These three regions are part of the major energy bases within China with significant emission intensity. These emissions-intensive products are manufactured in regions with a high degree of pollution production and a disadvantage in terms of environmental performance. Thus, exports from these three regions increased both local and national primary $PM_{2.5}$ emissions. The southeast coast region and the Beijing-Tianjin region were located in the second quadrant, accordingly the imports from these regions have resulted in an increase in national $PM_{2.5}$ emissions however the local emissions were reduced. These two regions imported large amounts of products from the inland regions with relatively higher emissions intensity, e.g. north China. The third quadrant corresponded to a negative *BAE* and a negative *BEE*, meaning that inter-regional trade has positive environmental impacts at both the local and national levels. In terms of total inter-regional trade, there were no regions located in the third quadrant. This suggests that no region can reduce local emissions through inter-regional trade without increasing national emissions. The northeast and northwest regions were located in the fourth quadrant. The inter-regional trade in these two regions facilitated local direct emissions whilst producing a national primary $PM_{2.5}$ saving.

Fig. 4b presented the environmental effects of trade of final products. All regions were located in the third or fourth quadrants. The manufacturing sector is more advanced in coastal regions rather than in the inland regions. Final products were transferred from the coastal regions to the less developed regions with lower emissions intensity thereby resulting in national emissions savings. Because of the large difference in primary $PM_{2.5}$ emission intensity amongst regions the coastal regions were net importers of primary $PM_{2.5}$. Final products are in the main, transferred from coastal regions to inland regions; however, the net primary $PM_{2.5}$ transfer through trade of final products was in the opposite direction due to the greater primary $PM_{2.5}$ emission intensity of the inland regions. Accordingly, the *BEE*s were positive in the central, northeast and southwest regions.

Fig. 4c and d presented the environmental effects from trade of intermediate products, which comprised the largest share of the total trade in China. The environmental effects of inter-regional trade within China were mainly determined by the trade of intermediate products. The northwest and northeast were located relatively upstream of production networks in China and imported downstream products from coastal regions with relatively lower emission intensity. Therefore, the inter-regional trade of intermediate products for the last stage of production corresponded to negative *BAE*s, as shown in Fig. 4c. Fig. 4d presented the environmental effects of T_v. All regions were generally located in the first or second quadrant. This is because the inland regions with relatively higher emissions intensity provide a large amount of raw materials to support the production in the coastal regions with relatively lower emissions intensity. Through the value chain related trades, the net primary $PM_{2.5}$ was mainly transferred from inland regions to coastal regions thereby contributing to an increase in national emissions.

According to formula (4), the aggregation of *BEE* for all regions is

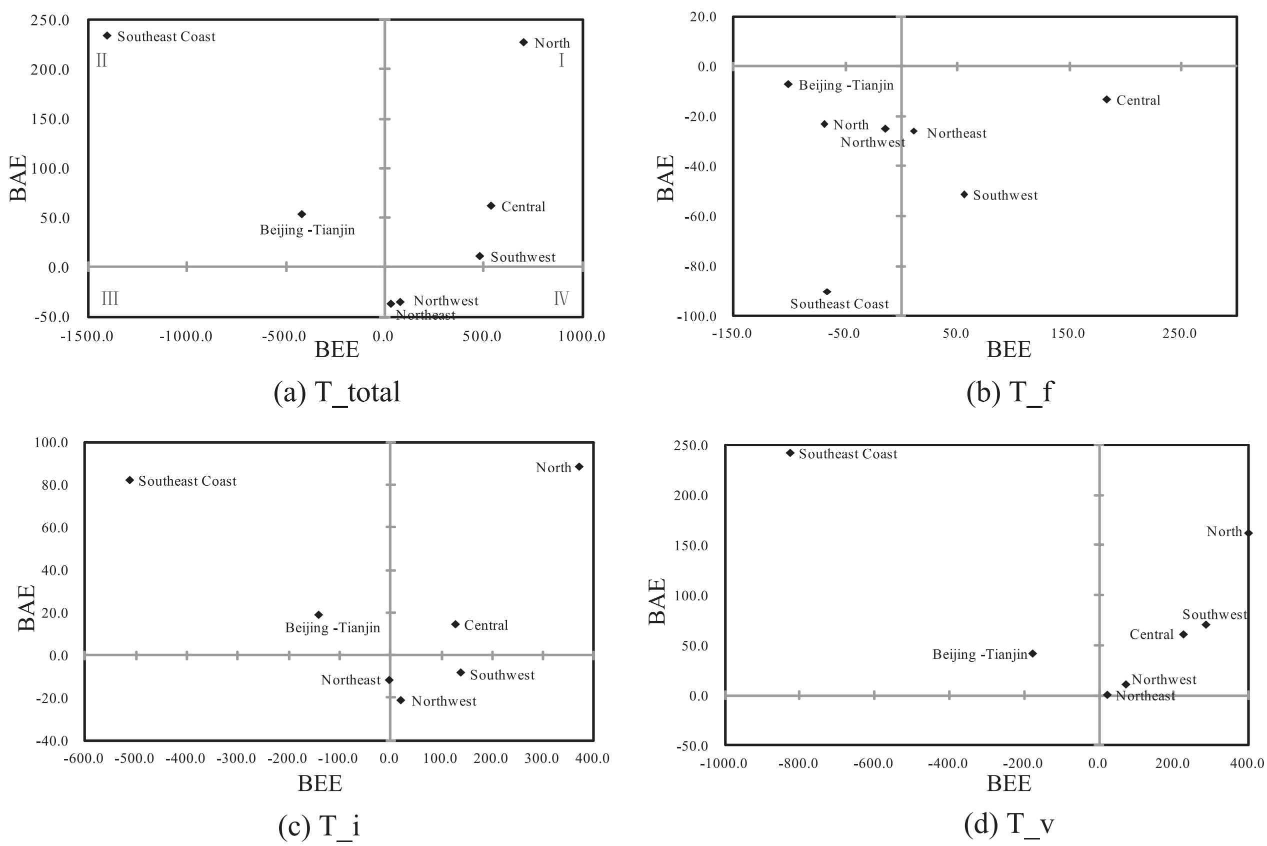

Fig. 4. The effects of inter-regional trade on the regional and national primary $PM_{2.5}$ in 2010 (unit: kt), a-d. The similar effects. analysis of SO_2, NO_x and NMVOC see Fig. E.1–E.3 in Appendix E. Corresponding data information also see Table E.1.

always zero ($\sum_s^G BEE^s = 0$) (see Table 2) because the positive and negative *BEE* flows offset with each other. According to formula (15), the sum of *BAE* for all regions reflects the additional emissions due to trade activities' intensity effect. A positive *BAE* means that the trade pattern contributes to an increase in national gross emissions because products are exported from regions with higher emissions intensity (e.g. developing regions) to those with lower emissions intensity (e.g. developed regions). In contrast, a negative *BAE* means this trade pattern contributes to a decrease in national gross emissions because products are exported from regions with lower emissions intensity (e.g. developed regions) to those with higher emissions intensity (e.g. developing regions). Therefore, the *BAE* simply reflects the environmental contribution of intensity effect embodied in trade activities. As shown in Table 2, the trade pattern T_f corresponded to a negative *BAE*. This means that this trade pattern generated national emissions savings thereby rejecting the pollution haven hypothesis. For primary $PM_{2.5}$, SO_2 and NO_x, the *BAE*s of T_i and T_v were positive. This indicated that these two kinds of trade increased national emissions while T_v had a greater effect than T_i. The sum of the three trade patterns (T_total) had positive *BAE*s, which means that inter-regional trade contributed to an increase in national emissions and supported the pollution haven hypothesis. Unlike the other three pollutants, NMVOC indicated negative *BAE*s for T_i and T_total. This is arguably due to different sources of NMVOC, thereby warranting further study.

Table 2
The sum of *BEE* and *BAE* in all regions of four air pollutants (unit: kt).

Trade	Pollutants				
	BEE	*BAE*			
	(Primary $PM_{2.5}$, SO_2, NO_x and NMVOC)	Primary $PM_{2.5}$	SO_2	NO_x	NMVOC
T_f	0	−236.0	−504.9	−337.7	−247.4
T_i	0	163.1	359.3	20.2	−131.9
T_v	0	589.2	1241.1	415.3	6.1
T_total	0	516.2	1095.5	97.8	−373.3

4. Discussion and conclusions

This study showed that the trade of intermediate products due to spatial production fragmentation caused additional emissions whereas the trade of final products decreased the national $PM_{2.5}$ related emissions within China. This is entirely different from the condition at global level (Zhang et al., 2017b). In China, the $PM_{2.5}$ related emission flows embodied in the final products trade had different spatial characteristics from those in the intermediate products trade.

The results of this paper are also different from the research from Zhao et al. (2015). Their results showed that $PM_{2.5}$ related emissions embodied in intermediate products make up a large portion of total emissions embodied in interprovincial trade of China in 2007. This study further revealed the effects of the intermediate products trade for the traditional intermediate products trade (T_i) and the domestic and global value chain (T_v). This research is the foundation for decomposition effects of supply chain for regional embodied $PM_{2.5}$ emission. Moreover, the environmental effects of three trade patterns were compared by *BEE* and *BAE*, and results showed that the trade of intermediate products from inland regions to coastal regions in China contributed to additional $PM_{2.5}$ related emissions thereby being in line with the pollution haven hypothesis. In contrast, the trade of final products from coastal regions to inland regions generated savings in $PM_{2.5}$ related emissions. Based on the results of this study, the following trade policies are proposed.

Firstly, among three trade patterns, the intermediate products trade derived from production fragmentation is the biggest contributor to $PM_{2.5}$ related emissions. The spatial production fragmentation is reshaping the inter-regional trade pattern significantly in China. The environmental provisions in the trade policy should not only focus on the traditional trade pattern but also target the fast-developing trade of intermediate products, which has resulted in more emissions. Moreover, the differences between regions in terms of trade patterns should be taken into consideration when the national government assigns emissions quota to regions. The regional responsibility for pollution is very complicated. For instance, in terms of intermediate products trade pattern, as an exporter, the North China emitted massive amount of $PM_{2.5}$ related emissions because of manufacturing intermediate products for other regions. However, it was also an importer in terms of the final products trade pattern. The central and southeast region of China emitted $PM_{2.5}$ related emissions for manufacturing final products for North China.

Secondly, it is imperative to avoid “emission leakage” in the domestic trade. The trade policy should encourage products to be imported from the regions with lower pollutant emissions intensity. This will motivate exporters to reduce pollutant emissions intensity through the technological innovation. Meanwhile, the national government should provide more financial and technical support for those regions that export intermediate products to reduce their emission intensity.

It is necessary to bridge the gap between the intensity of inland and coastal regions. In addition, the Chinese government has released “Belt and Road Initiatives”, which may have implications on the unequal exchange of air pollution and economic benefits along the domestic supply chains (Zhang et al., 2018). According to results of this paper, inland regions in China should also take the opportunity of Belt and Road Initiatives to adjust economic structures to reduce the emission intensity.

These findings provide a useful reference for other countries to analyze the environmental effects of domestic trade. One limitation of this study is that only four kinds of embodied air pollutants are considered among regions. Future research opportunities exist to further investigate other kinds of pollutants' sectoral emissions derived from different trade patterns.

Notes

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Appendix F. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jclepro.2018.05.195.

Appendix A. Methodology of the multi-regional input-output model

Z^{sr} represents the intermediate input matrix from region$s(s = 1, \cdots, g)$ to region $r(r = 1, \cdots, g)$, the element $z_{ij}^{sr}(i = j = 1, \cdots, n)$ represents the transfer from sector $i$of region$s$to sector j of region$r$. Y^{sr}represents the final demand of region$r$for products from region$s$, represents the final output of region$s$, VA^srepresents the value added of region$s$.

Each region's outputs are used to satisfy intermediate or final consumption; the multi-regional input-output table analysis framework begins with an accounting balance of monetary flow.

$$\begin{bmatrix} X^1 \\ X^2 \\ \vdots \\ X^g \end{bmatrix} = \begin{bmatrix} A^{11} & A^{12} & \cdots & A^{1g} \\ A^{21} & A^{22} & \cdots & A^{2g} \\ \vdots & \vdots & \ddots & \vdots \\ A^{g1} & A^{g2} & \cdots & A^{gg} \end{bmatrix} \begin{bmatrix} X^1 \\ X^2 \\ \vdots \\ X^g \end{bmatrix} + \begin{bmatrix} \sum_r^G Y^{1r} + EX^1 \\ \sum_r^G Y^{2r} + EX^2 \\ \vdots \\ \sum_r^G Y^{gr} + EX^g \end{bmatrix} \tag{A.1}$$

where $A^{sr}$is the input coefficient matrix that represents the intermediate use in region $r$of goods produced in region$s$. The elements of the input coefficient matrix satisfy $a_{ij}^{sr} = z_{ij}^{sr}/x_j^r$. Equation (A.1) can be rearranged as,

$$\begin{bmatrix} X^1 \\ X^2 \\ \vdots \\ X^g \end{bmatrix} = \begin{bmatrix} B^{11} & B^{12} & \cdots & B^{1g} \\ B^{21} & B^{22} & \cdots & B^{2g} \\ \vdots & \vdots & \ddots & \vdots \\ B^{g1} & B^{g2} & \cdots & B^{gg} \end{bmatrix} \begin{bmatrix} \sum_r^G Y^{1r} \\ \sum_r^G Y^{2r} \\ \vdots \\ \sum_r^G Y^{gr} \end{bmatrix} \begin{bmatrix} \sum_r^G Y^{1r} + EX^1 \\ \sum_r^G Y^{2r} + EX^2 \\ \vdots \\ \sum_r^G Y^{gr} + EX^g \end{bmatrix} \tag{A.2}$$

where B^{sr}, the Leontief inverse, represents the quantity of the gross output of region$s$for a one-unit increase in the final demand of region$r$. From equation (A.2), the final output of region $r$is as follows:

$$X^r = \sum_t^G B^{rt} \sum_u^G Y^{tu} + \sum_t^G B^{rt} EX^t \tag{A.3}$$

The intermediate input of region$r$from region$s$is$Z^{sr} = A^{sr}X^r$. The exports from region$s$to region$r$are $T^{sr} = Y^{sr} + A^{sr}X^r$. According to Zhang et al.'s study (2017b), $B^{rr} = L^{rr} + L^{rr}\sum_{t \neq s}^G A^{rt}B^{tr}$.Consequently, equation (A.4) can be obtained from equation (A.3):

$$T^{sr} = \underbrace{Y^{sr}}_{T\_f^{sr}} + \underbrace{A^{sr}L^{rr}Y^{rr}}_{T\_i^{sr}} + \underbrace{A^{sr}L^{rr}\sum_{t \neq r}^G A^{rt}B^{tr}Y^{rr} + A^{sr}\sum_{t \neq r}^G B^{rt}Y^{tr} + A^{sr}\sum_t^G B^{rt}\sum_{u \neq r}^G Y^{tu} + A^{sr}\sum_t^G B^{rt}EX^t}_{T\_v^{sr}} \tag{A.4}$$

where T_f^{sr} defines trade of final products. The trade partner would directly absorb the exported products, and the exporter is located in the last stage of productions. T_i^{sr} is the traditional Ricardian trade of intermediate products for the last stage of production, which need to be further processed by the trade partner before finally absorbed by the trade partner. The last term in equation (A.4) are the narrowly defined value chain related trade (Zhang et al., 2017b). The traded products cross the regional or national border more than once, which may be finally absorbed by a domestic region or further processed and exported to foreign counties. The former is named the trade of intermediate products related with domestic value chain, and the latter is named the trade of intermediate products related with global value chain.

Based on the balance of gross output $X^s = A^{ss}X^s + Y^{ss} + \sum_{s\neq r}^{M} T^{sr} + EX^s$, gross output generated from each region can be decomposed into different components:

$$X^s = L^{ss}Y^{ss} + L^{ss}EX^s + L^{ss}\sum_{s\neq r}^{G} T\_f^{sr} + L^{ss}\sum_{s\neq r}^{G} T\_i^{sr} + L^{ss}\sum_{s\neq r}^{G} T\_v^{sr} \tag{A.5}$$

The gross output of regionsis decomposed into five terms. The first term represents the output induced by the domestic final demand through local industrial linkage, which has no relation with the inter-regional production fragmentation. The second and third terms represent the outputs induced by trade in final products, which are absorbed by the foreign countries or other regions directly. The fourth term represents the trade in intermediate products, which is further processed and absorbed by the trade partner. The last term represent the domestic and global value chain related trade.

Tables mentioned in the Data sources and Methodology see Table A.1-A.3.

Table A.1
Region divisions.

Region	*Provinces, municipalities that included in each region*
Beijing-Tianjin	Beijing, Tianjin
north	Hebei, Shanxi, Inner Mongolia, Shaanxi
northeast	Liaoning, Jilin, Heilongjiang
southeast coast	Shanghai, Jiangsu, Zhejiang, Fujian, Guangdong, Shandong
central	Anhui, Jiangxi, Henan, Hubei, Hunan
southwest	Chongqing, Sichuan, Guizhou, Yunnan, Guangxi, Hainan
northwest	Gansu, Qinghai, Ningxia, Xinjiang

Table A.3
The meaning of different variables.

Variables	Definition
Z	Intermediate inputs
X	Outputs
Y	Final Goods
A	Input Coefficient
B	Leontief Inverse
L	Local Leontief Inverse
T	Trade
T_f	Trade of final products
T_i	Trade of intermediate products for the last stage of production
T_v	Trade for the domestic and global value chain
T_total	Total inter-regional trade
E	Emissions
F	Emission Coefficient
EEX	Emissions embodied in exports
BEE	Balance of embodied emissions
EAI	Emissions avoided by imports
BAE	Balance of avoided emissions

Appendix B. Detailed data for decomposition of air pollutants emissions See Table B.1.

Table B.1
The detailed decomposition of gross $PM_{2.5}$ related emissions embodied in export among the seven regions in 2010 (unit: kt).

Pollutants	Regions	International Export	Inter-regional Export		
			T_f	T_i	T_v
Primary $PM_{2.5}$	Beijing-Tianjin	39.6	36.1	33.2	36.7
	north	161.7	211.9	561.8	684.5
	northeast	144.5	140.5	163.4	177.3
	southeast coast	713.5	253.5	249.7	292.6
	central	233.3	346.9	362.2	430.1
	southwest	195.1	194.7	284.9	383.8
	northwest	51.1	41.1	85.9	112.2
SO_2	Beijing-Tianjin	103.5	113.1	123.2	149.3
	north	312.4	478.3	1355.6	1729.4
	northeast	295.4	398.6	507.1	609
	southeast coast	2125.8	875.2	860.6	1041.1
	central	397.4	711.9	752	896.9
	southwest	220.2	315	435.1	562.6
	northwest	79.6	120.4	246.4	326.7
NO_x	Beijing-Tianjin	58.3	59.4	75.5	90.9
	north	299.5	506.9	1446	1883.9
	northeast	186.8	286.7	361.8	423
	southeast coast	1651.5	722.2	702.7	840.3
	central	391.5	691.2	776.7	930.6
	southwest	305.4	608.8	782.6	993.4
	northwest	73.1	121	248.3	328.6
NMVOC	Beijing-Tianjin	105.1	108.8	97.5	115.6
	north	179.2	313.1	581.9	708.5
	northeast	197.4	271.5	306.5	355.9
	southeast coast	1923.3	759	680.4	810.5
	central	277.4	485.6	414.9	484.5
	southwest	201.1	311.9	300.4	378
	northwest	51.3	102.7	160.8	211.6

Table A.2
Multi-regional input-output table.

Inputs			Outputs							
			Intermediate demand			Final demand			Exports	Output
			Region 1	⋯	Region g	Region 1	⋯	Region g		
			Sector1 … Sector n		Sector1 … Sector n	Sector1 … Sector n		Sector1 … Sector n		
Intermediate inputs	Region 1	Sector 1 ⋮ Sector n	Z^{11}	⋯	Z^{1g}	Y^{11}	⋯	Y^{1g}	EX^1	X^1
	⋮		⋮	⋱	⋮	⋮	⋱	⋮	⋮	⋮
	Region g	Sector 1 ⋮ Sector n	Z^{g1}	⋯	Z^{gg}	Y^{g1}	⋯	Y^{gg}	EX^g	X^g
Imports			IMI^1	⋯	IMI^g	IMF^1	⋯	IMF^g		
Value added			VA^1	⋯	VA^g					
Output			$(X^1)^T$	⋯						

Appendix C. The *BEE* flows and corresponding data information See Figs. C.1–C.3 and Table C.1.

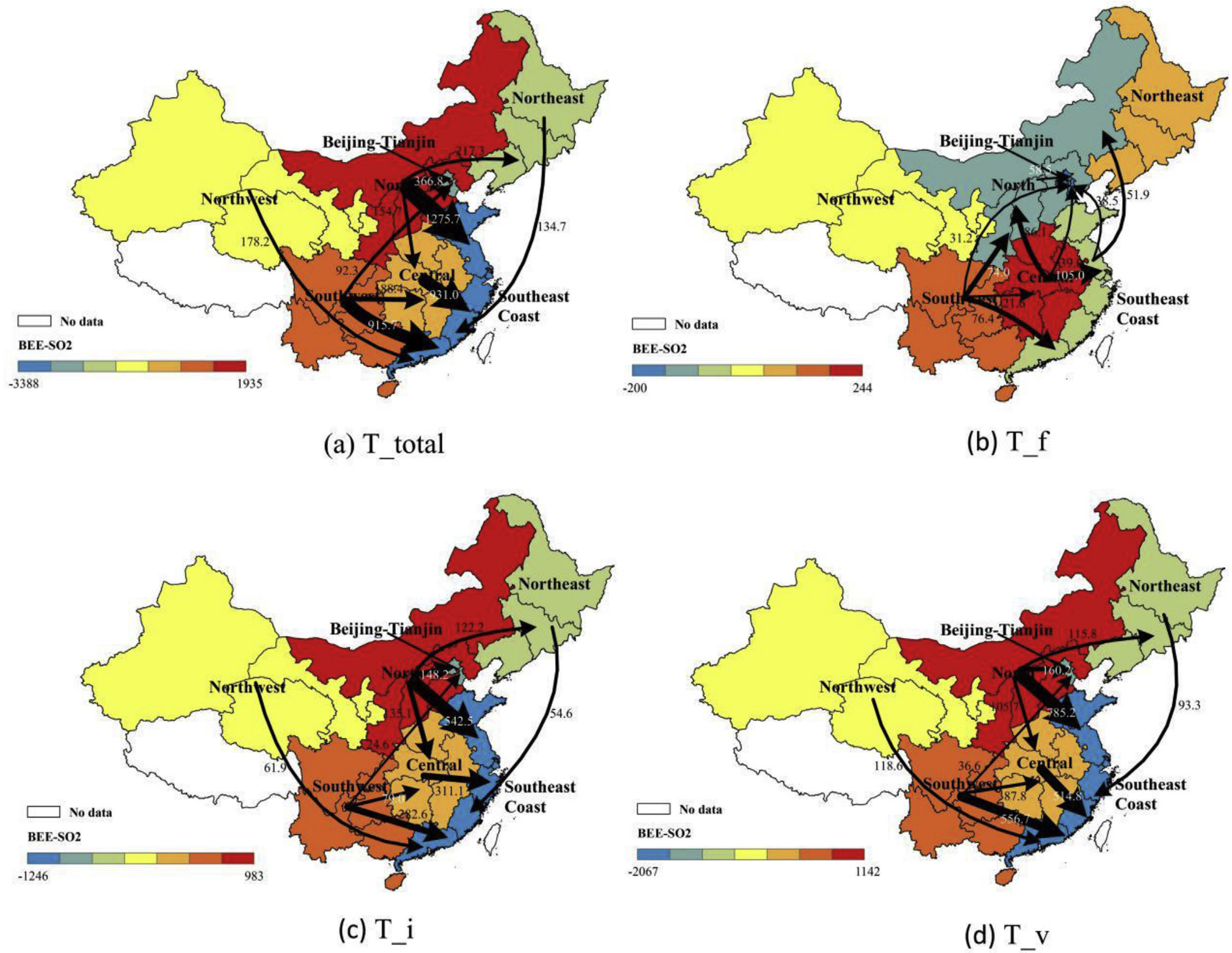

Fig. C.1. The top 10 inter-regional SO_2 *BEE* flows of three trade patterns among seven regions in 2010 (unit of flows: kt), a-d. Corresponding data information see Table C.1.

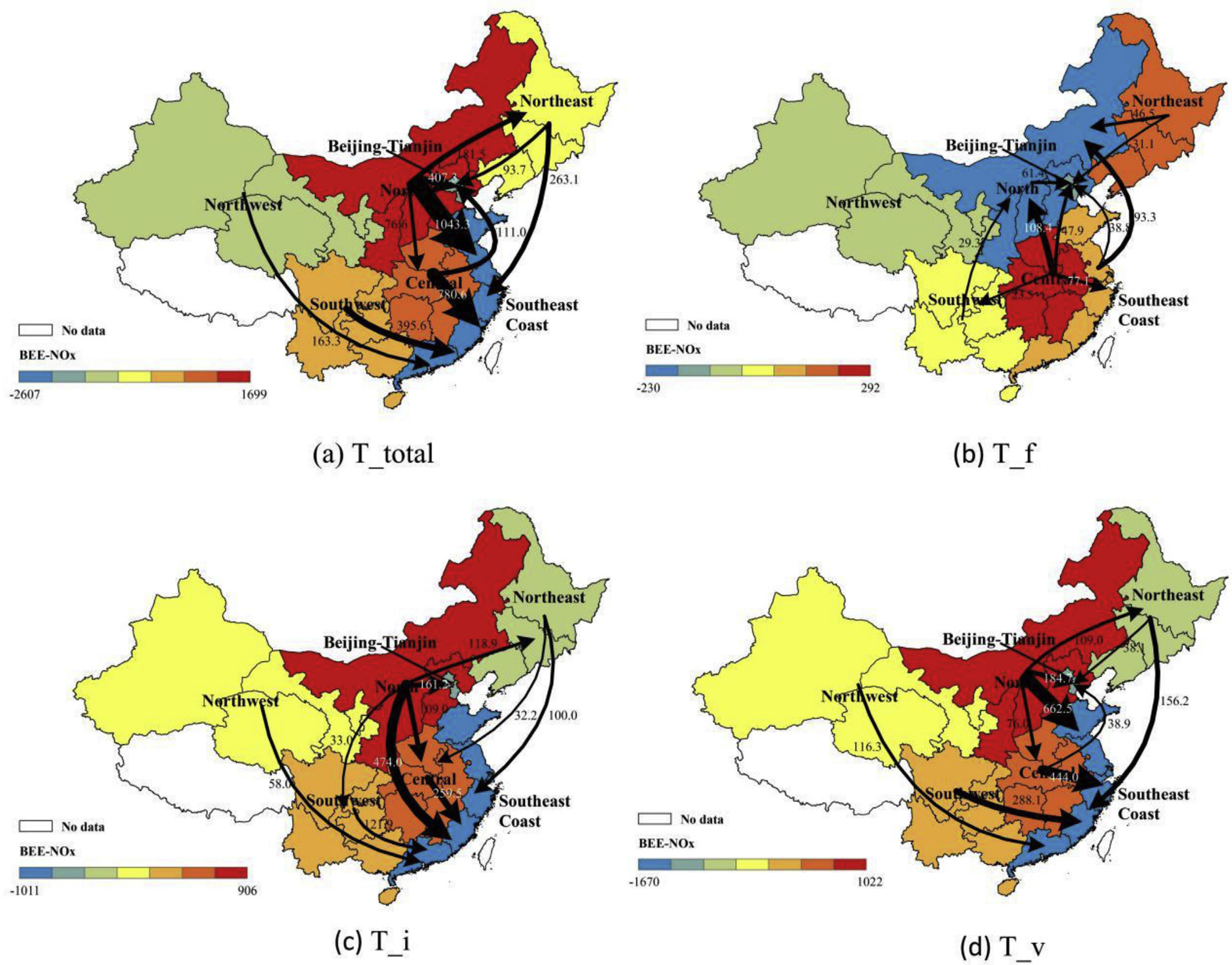

Fig. C.2. The top 10 inter-regional NO_x *BEE* flows of three trade patterns among seven regions in 2010 (unit of flows: kt), a-d. Corresponding data information see Table C.1.

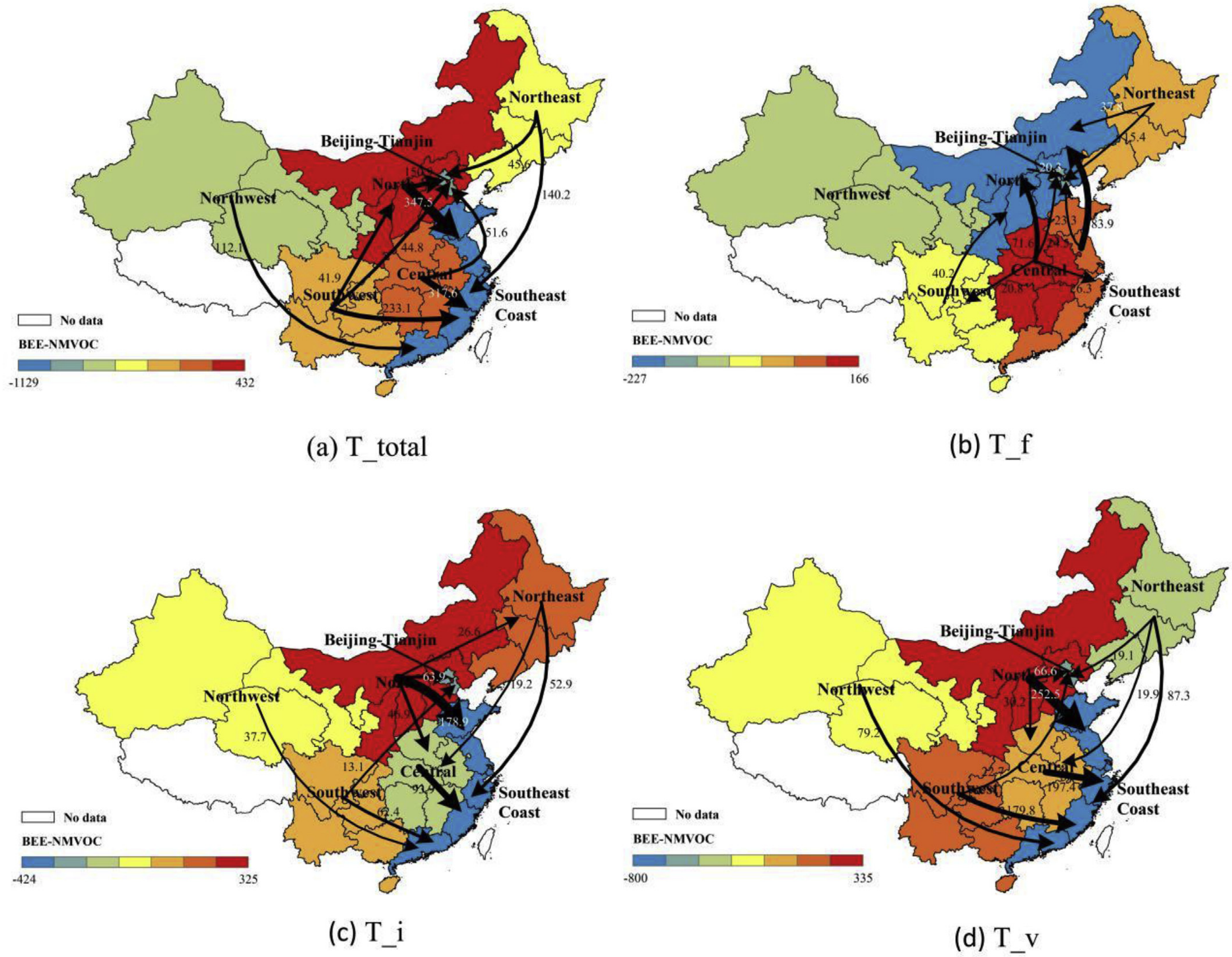

Fig. C.3. The top 10 inter-regional NMVOC *BEE* flows of three trade patterns among seven regions in 2010 (unit of flows: kt), a-d. Corresponding data information see Table C.1.

Table C.1
Top 10 inter-regional PM2.5 related BEE transfer flows of three trade patterns among seven regions in 2010 (unit of flows: kt). This table corresponds to the emission flows in Fig. 3 and C.1–C.3.

Pollutants	T_f		T_i		T_v		T_total	
	Bilateral trade	*BEE* (kt)	Bilateral trade	*BEE* (kt)	Bilateral trade	*BEE* (kt)	Bilateral trade	*BEE* (kt)
Primary $PM_{2.5}$	central-southeast coast	62.8	north-southeast coast	201.9	north-southeast coast	278.8	north-southeast coast	473.4
	central-north	54.6	central-southeast coast	151.8	central-southeast coast	235.4	central-southeast coast	450.1
	central-Beijing-Tianjin	31.3	southwest-southeast coast	114.4	southwest-southeast coast	230.1	southwest-southeast coast	367.1
	north-Beijing-Tianjin	30.3	north-Beijing-Tianjin	78.0	north-Beijing-Tianjin	83.5	north-Beijing-Tianjin	191.8
	southwest-north	26.2	north-northeast	42.2	northwest-southeast coast	49.2	central-Beijing-Tianjin	84.9
	southwest-southeast coast	22.6	north-central	38.6	northeast-southeast coast	36.0	northwest-southeast coast	72.5
	southwest-Beijing-Tianjin	15.0	northeast-southeast coast	24.6	north-northeast	33.0	north-northeast	64.3
	central-northwest	13.3	northwest-southeast coast	24.0	central-Beijing-Tianjin	32.0	southwest-Beijing-Tianjin	63.5
	central-southwest	11.6	central-Beijing-Tianjin	21.6	southwest-Beijing-Tianjin	29.7	northeast-southeast coast	59.4
	northeast-north	11.0	southwest-Beijing-Tianjin	18.7	north-central	21.8	northeast-Beijing-Tianjin	38.0
SO_2	central-southeast coast	105.0	north-southeast coast	542.5	north-southeast coast	785.2	north-southeast coast	1275.7
	central-north	86.1	central-southeast coast	311.1	southwest-southeast coast	556.7	central-southeast coast	931.0
	southwest-southeast coast	76.4	southwest-southeast coast	282.6	central-southeast coast	514.8	southwest-southeast coast	915.7
	southwest-north	74.0	north-Beijing-Tianjin	148.2	north-Beijing-Tianjin	160.2	north-Beijing-Tianjin	366.8
	north-Beijing-Tianjin	58.5	north-central	135.1	northwest-southeast coast	118.6	north-northeast	217.3
	southeast coast-north	51.9	north-northeast	122.2	north-northeast	115.8	southwest-central	188.4
	central-Beijing-Tianjin	39.0	southwest-central	79.0	north-central	105.7	northwest-southeast coast	178.2

(*continued on next page*)

Table C.1 (*continued*)

Pollutants	T_f		T_i		T_v		T_total	
	Bilateral trade	*BEE* (kt)	Bilateral trade	*BEE* (kt)	Bilateral trade	*BEE* (kt)	Bilateral trade	*BEE* (kt)
	southeast coast-Beijing-Tianjin	38.5	northwest-southeast coast	61.9	northeast-southeast coast	93.3	north-central	154.7
	southwest-Beijing-Tianjin	31.2	northeast-southeast coast	54.6	southwest-central	87.8	northeast-southeast coast	134.7
	southwest-central	21.6	southwest-Beijing-Tianjin	24.6	southwest-Beijing-Tianjin	36.6	southwest-Beijing-Tianjin	92.3
NO_x	central-north	108.4	north-southeast coast	474.0	north-southeast coast	662.5	north-southeast coast	1043.3
	southeast coast-north	93.3	central-southeast coast	259.5	central-southeast coast	444.0	central-southeast coast	780.6
	central-southeast coast	77.1	north-Beijing-Tianjin	161.2	southwest-southeast coast	288.1	north-Beijing-Tianjin	407.3
	north-Beijing-Tianjin	61.4	southwest-southeast coast	121.9	north-Beijing-Tianjin	184.7	southwest-southeast coast	395.6
	central-Beijing-Tianjin	47.9	north-northeast	118.9	northeast-southeast coast	156.2	northeast-southeast coast	263.1
	northeast-north	46.5	north-central	109.0	northwest-southeast coast	116.3	north-northeast	181.5
	southeast coast-Beijing-Tianjin	38.8	northeast-southeast coast	100.0	north-northeast	109.0	northwest-southeast coast	163.3
	northeast-Beijing-Tianjin	31.1	northwest-southeast coast	58.0	north-central	76.0	central-Beijing-Tianjin	111.0
	southwest-north	29.3	north-southwest	33.0	central-Beijing-Tianjin	38.9	northeast-Beijing-Tianjin	93.7
	central-southwest	23.5	northeast-central	32.2	northeast-Beijing-Tianjin	38.1	north-central	76.6
NMVOC	southeast coast-north	83.9	north-southeast coast	178.9	north-southeast coast	252.5	north-southeast coast	347.5
	central-north	71.6	central-southeast coast	93.9	central-southeast coast	197.4	central-southeast coast	317.6
	southwest-north	40.2	north-Beijing-Tianjin	63.9	southwest-southeast coast	179.8	southwest-southeast coast	233.1
	northeast-north	37.8	southwest-southeast coast	62.4	northeast-southeast coast	87.3	north-Beijing-Tianjin	150.9
	central-southeast coast	26.3	northeast-southeast coast	52.9	northwest-southeast coast	79.2	northeast-southeast coast	140.2
	central-Beijing-Tianjin	24.5	north-central	46.9	north-Beijing-Tianjin	66.6	northwest-southeast coast	112.1
	southeast coast-Beijing-Tianjin	23.3	northwest-southeast coast	37.7	northeast-central	30.2	central-Beijing-Tianjin	51.6
	central-southwest	20.8	north-northeast	26.6	southwest-Beijing-Tianjin	22.7	northeast-Beijing-Tianjin	45.6
	north-Beijing-Tianjin	20.3	northeast-central	19.2	northeast-central	19.9	southwest-Beijing-Tianjin	44.8
	northeast-Beijing-Tianjin	15.4	southwest-Beijing-Tianjin	13.1	northeast-Beijing-Tianjin	19.1	southwest-north	41.9

Appendix D. The contribution analysis of scale effect and intensity effect. See Table D.1-D.3.

Table D.1
Contribution of scale effect and intensity effect of SO_2 in different trade patterns.

T_f					T_i					T_v				
Start	End	ΔT(s,r) / BEE^{sr}	ΔI(s,r) / BEE^{sr}	$T^{sr}-T^{rs}$ (billion yuan)	Start	End	ΔT(s,r) / BEE^{sr}	ΔI(s,r) / BEE^{sr}	$T^{sr}-T^{rs}$ (billion yuan)	Start	End	ΔT(s,r) / BEE^{sr}	ΔI(s,r) / BEE^{sr}	$T^{sr}-T^{rs}$ (billion yuan)
central (40%)	north (15%)	1.02	-0.02	191	north (54%)	central (8%)	0.67	0.33	105	north (44%)	central (4%)	0.57	0.43	66
	southeast coast (18%)	-0.31	1.31	-99		northeast (7%)	0.53	0.47	80		northeast (4%)	0.33	0.67	44
	Beijing-Tianjin (7%)	-0.10	1.10	-19		southeast coast (31%)	0.45	0.55	328		southeast coast (30%)	0.48	0.52	486
southwest (35%)	north (13%)	0.75	0.25	87		Beijing-Tianjin (8%)	0.47	0.53	132		Beijing-Tianjin (6%)	0.43	0.57	126
	southeast coast (13%)	-1.19	2.19	-272	southwest (21%)	central (4%)	0.10	0.90	8	southwest (27%)	central (3%)	0.24	0.76	20
	Beijing-Tianjin (5%)	-0.60	1.60	-79		southeast coast (16%)	0.02	0.98	9		southeast coast (22%)	0.38	0.62	283
	central (4%)	-2.88	3.88	-98		Beijing-Tianjin (1%)	0.04	0.96	3		Beijing-Tianjin (2%)	0.31	0.69	28
southeast coast (15%)	north (9%)	3.38	-2.38	491	central (18%)	southeast coast (18%)	0.28	0.72	148	central (20%)	southeast coast (20%)	0.51	0.49	436
	Beijing-Tianjin (6%)	-0.19	1.19	-53	northeast (3%)	southeast coast (3%)	0.28	0.72	32	northeast (4%)	southeast coast (4%)	0.54	0.46	94
north (10%)	Beijing-Tianjin (10%)	-0.23	1.23	-51	northwest (4%)	southeast coast (4%)	0.06	0.94	6	northwest (5%)	southeast coast (5%)	0.50	0.50	92

Table D.2
Contribution of scale effect and intensity effect of NO_x in different trade patterns.

T_f

Start	End	$\Delta T(s,r)$ / BEE^{sr}	$\Delta I(s,r)$ / BEE^{sr}	$T^{sr} - T^{rs}$ (billion yuan)
central (46%)	north (19%)	0.83	0.17	191
	southwest (4%)	1.79	-0.79	98
	southeast coast (14%)	-0.46	1.46	-99
	Beijing-Tianjin (9%)	-0.12	1.12	-19
southeast coast (24%)	north (17%)	1.98	-0.98	491
	Beijing-Tianjin (7%)	-0.30	1.30	-53
northeast (14%)	north (8%)	1.15	-0.15	93
	Beijing-Tianjin (6%)	-0.09	1.09	-8
north (11%)	Beijing-Tianjin (11%)	-0.31	1.31	-51
southwest (5%)	north (5%)	1.18	-0.18	87

T_i

Start	End	$\Delta T(s,r)$ / BEE^{sr}	$\Delta I(s,r)$ / BEE^{sr}	$T^{sr} - T^{rs}$ (billion yuan)
north (61%)	central (8%)	0.80	0.20	105
	northeast (8%)	0.64	0.36	80
	southeast coast (32%)	0.51	0.49	328
	Beijing-Tianjin (11%)	0.54	0.46	132
	southwest (2%)	0.46	0.54	23
central (18%)	southeast coast (18%)	0.35	0.65	148
northeast (9%)	southeast coast (7%)	0.20	0.80	32
	central (2%)	0.40	0.60	19
southwest (8%)	southeast coast (8%)	0.04	0.96	9
northwest (4%)	southeast coast (4%)	0.07	0.93	6

T_v

Start	End	$\Delta T(s,r)$ / BEE^{sr}	$\Delta I(s,r)$ / BEE^{sr}	$T^{sr} - T^{rs}$ (billion yuan)
north (48%)	southeast coast (31%)	0.56	0.44	486
	central (3%)	0.76	0.24	66
	northeast (5%)	0.43	0.57	44
	Beijing-Tianjin (9%)	0.50	0.50	126
central (23%)	southeast coast (21%)	0.61	0.39	436
	Beijing-Tianjin (2%)	0.33	0.67	23
southwest (14%)	southeast coast (14%)	0.54	0.46	283
northeast (9%)	southeast coast (7%)	0.42	0.58	94
	Beijing-Tianjin (2%)	0.42	0.58	31
northwest (6%)	southeast coast (6%)	0.56	0.44	92

Table D.3
Contribution of scale effect and intensity effect of NMVOC in different trade patterns.

T_f

Start	End	$\Delta T(s,r)$ / BEE^{sr}	$\Delta I(s,r)$ / BEE^{sr}	$T^{sr} - T^{rs}$ (billion yuan)
central (40%)	north (20%)	0.88	0.12	191
	southwest (6%)	1.65	-0.65	98
	southeast coast (7%)	-1.02	2.02	-99
	Beijing-Tianjin (7%)	-0.17	1.17	-19
southeast coast (29%)	north (23%)	1.74	-0.74	491
	Beijing-Tianjin (6%)	-0.42	1.42	-53
northeast (14%)	north (10%)	0.87	0.13	93
	Beijing-Tianjin (4%)	-0.13	1.13	-8
southwest (11%)	north (11%)	0.90	0.10	87
north (6%)	Beijing-Tianjin (6%)	-0.61	1.61	-51

T_i

Start	End	$\Delta T(s,r)$ / BEE^{sr}	$\Delta I(s,r)$ / BEE^{sr}	$T^{sr} - T^{rs}$ (billion yuan)
north (54%)	central (8%)	0.97	0.03	105
	northeast (5%)	1.28	-0.28	80
	southeast coast (30%)	0.73	0.27	328
	Beijing-Tianjin (11%)	0.72	0.28	132
central (16%)	southeast coast (16%)	0.61	0.39	148
northeast (12%)	southeast coast (9%)	0.26	0.74	32
	central (3%)	0.45	0.55	19
southwest (12%)	southeast coast (10%)	0.06	0.94	9
	Beijing-Tianjin (2%)	0.07	0.93	6
northwest (6%)	southeast coast (6%)	0.08	0.92	3

T_v

Start	End	$\Delta T(s,r)$ / BEE^{sr}	$\Delta I(s,r)$ / BEE^{sr}	$T^{sr} - T^{rs}$ (billion yuan)
north (37%)	southeast coast (27%)	0.78	0.22	486
	central (3%)	0.96	0.04	66
	Beijing-Tianjin (7%)	0.70	0.30	126
southwest (21%)	southeast coast (19%)	0.64	0.36	283
	Beijing-Tianjin (2%)	0.45	0.55	28
central (21%)	southeast coast (21%)	0.85	0.15	436
northeast (13%)	southeast coast (9%)	0.50	0.50	94
	central (2%)	0.49	0.51	21
	Beijing-Tianjin (2%)	0.57	0.43	31
northwest (8%)	southeast coast (8%)	0.58	0.42	92

Appendix E. The environmental effects analysis of inter-regional trade and corresponding data information. See Figs. E.1–E.3 and Table E.1.

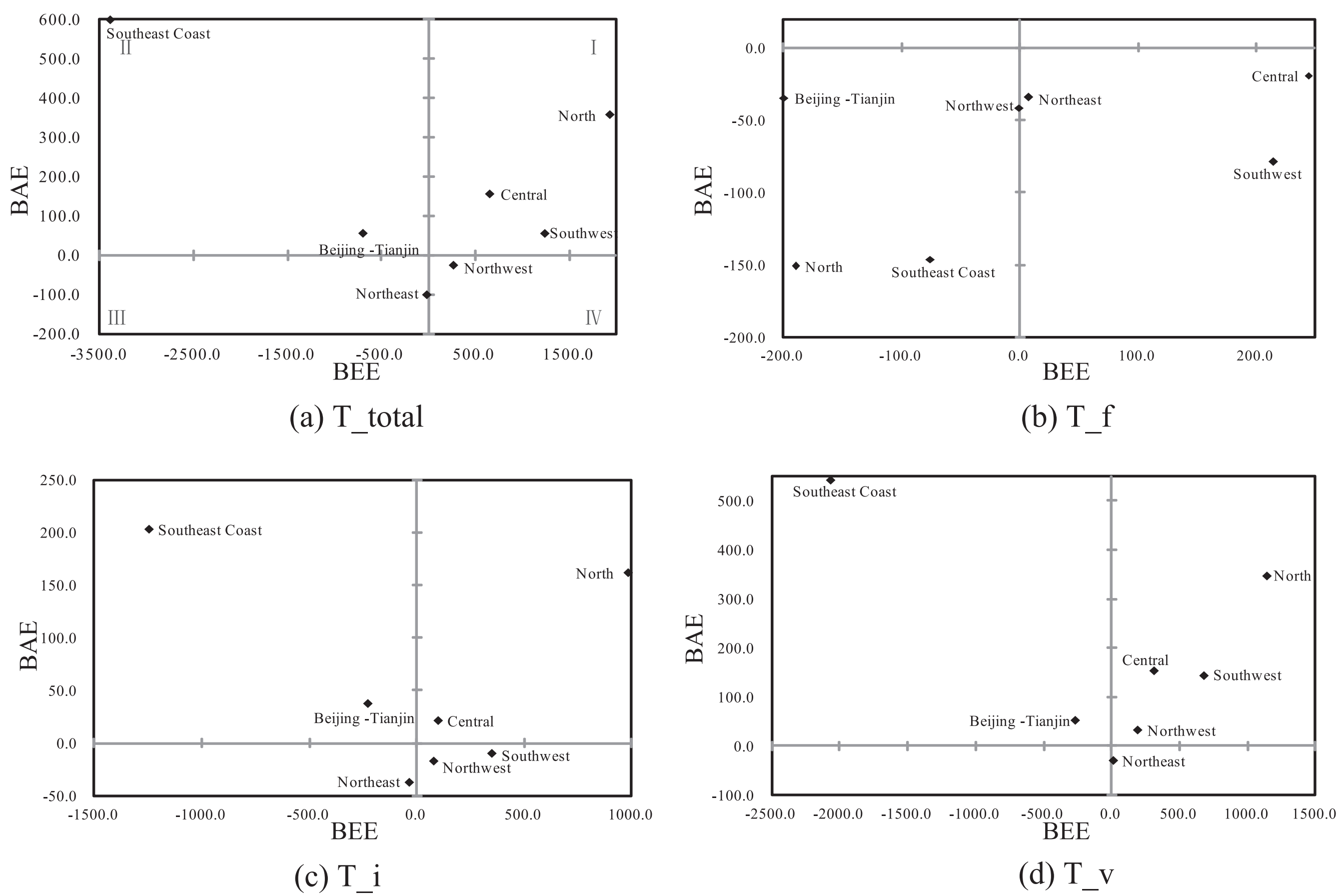

Fig. E.1. The effects of inter-regional trade on the regional and national SO_2 in 2010 (unit: kt).

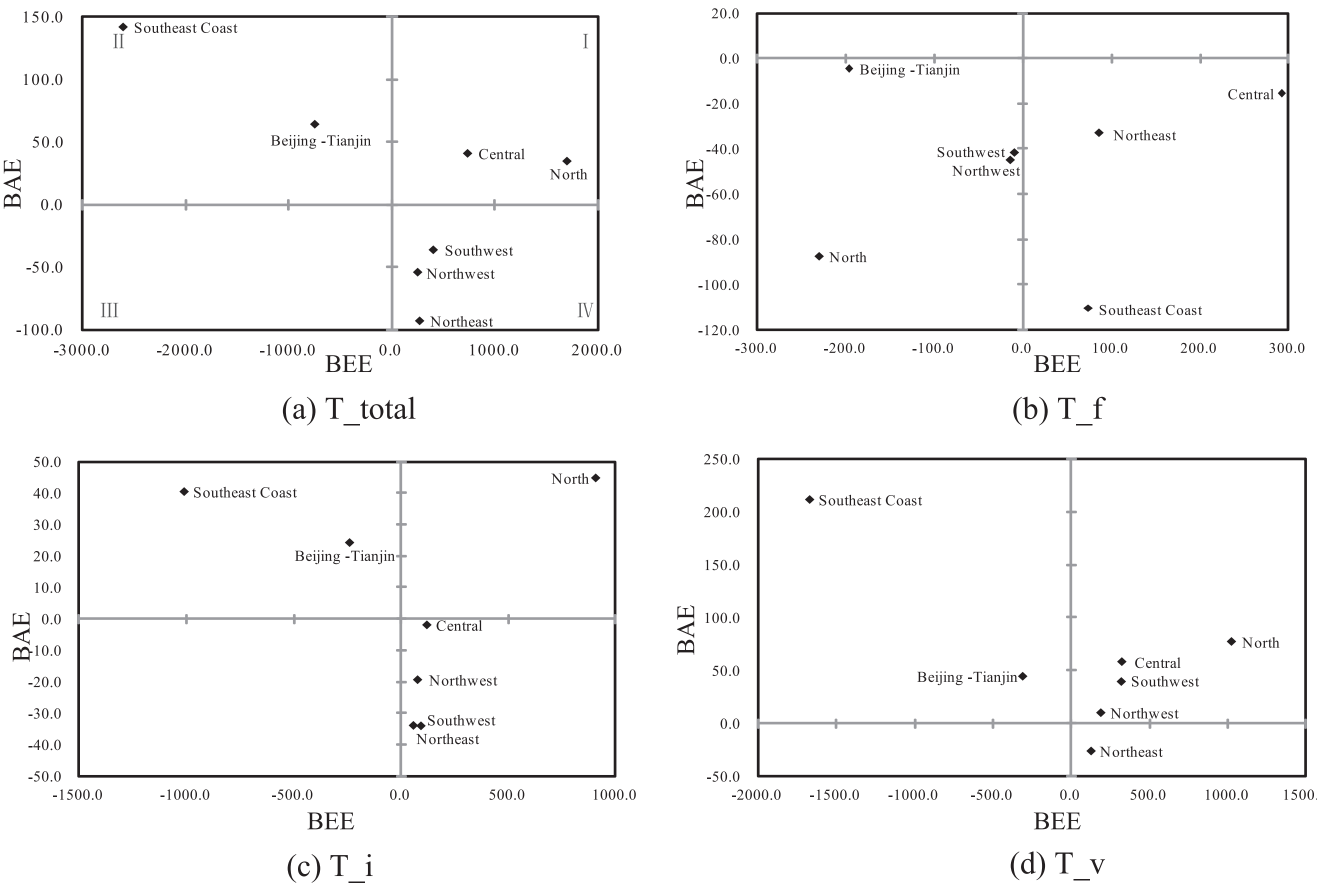

Fig. E.2. The effects of inter-regional trade on the regional and national NO_x in 2010 (unit: kt).

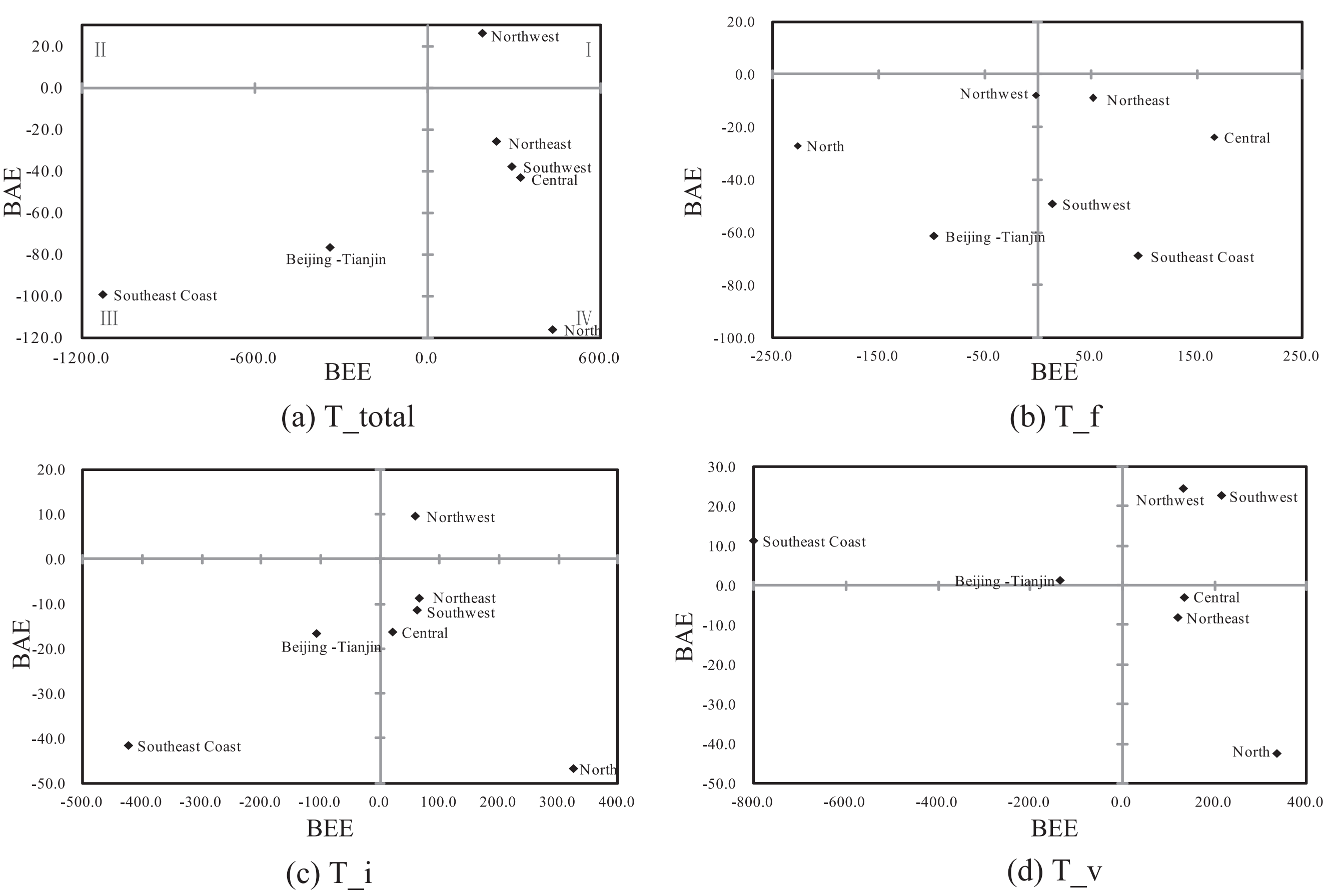

Fig. E.3. The effects of inter-regional trade on the regional and national NMVOC in 2010 (unit: kt).

Table E.1
Environmental effects of different trade patterns by the balance of embodied emissions (*BEE*) and avoided emissions (*BAE*) in 2010 (unit: kt). This table corresponds to the four quadrants in Fig. 4 and E.1-E.3.

Pollutants	Region	*BEE*				*BAE*			
		T_f	T_i	T_v	T_total	T_f	T_i	T_v	T_total
Primary $PM_{2.5}$	Beijing-Tianjin	−101.1	−141.3	−177.9	−420.3	−7.2	18.9	41.9	53.6
	north	−69.0	370.7	399.3	701.1	−23.1	88.4	162.0	227.4
	northeast	10.9	−2.6	21.9	30.2	−25.9	−11.7	0.6	−37.0
	southeast coast	−66.2	−512.3	−825.8	−1404.3	−90.2	82.1	242.1	234.1
	central	183.7	127.6	225.5	536.7	−13.3	14.5	60.9	62.1
	southwest	55.8	137.9	285.5	479.2	−51.3	−8.1	70.7	11.2
	northwest	−14.1	20.0	71.5	77.4	−25.1	−21.1	11.0	−35.2
SO_2	Beijing-Tianjin	−199.8	−227.9	−267.9	−695.6	−34.6	37.5	52.4	55.4
	north	−189.8	982.7	1141.7	1934.6	−150.8	161.7	346.6	357.4
	northeast	7.2	−35.2	12.4	−15.6	−34.2	−37.3	−29.5	−101.1
	southeast coast	−75.6	−1245.6	−2067.1	−3388.3	−146.1	203.0	541.9	598.8
	central	244.0	99.1	311.5	654.6	−19.1	21.3	153.4	155.6
	southwest	214.4	348.6	678.5	1241.6	−78.6	−9.9	143.5	55.0
	northwest	−0.3	78.4	190.7	268.8	−41.3	−17.1	32.7	−25.8
NO_x	Beijing-Tianjin	−197.1	−240.5	−309.8	−747.4	−4.6	24.2	44.5	64.1
	north	−229.9	906.3	1022.2	1698.7	−87.6	44.8	77.4	34.6
	northeast	86.0	56.8	126.8	269.7	−33.0	−33.9	−26.2	−93.1
	southeast coast	73.4	−1011.2	−1669.6	−2607.5	−110.2	40.4	211.6	141.8
	central	291.9	119.7	322.7	734.3	−15.6	−1.9	58.4	40.8
	southwest	−9.8	92.4	319.2	401.8	−41.8	−34.0	39.5	−36.3
	northwest	−14.5	76.5	188.5	250.5	−44.9	−19.4	10.1	−54.2
NMVOC	Beijing-Tianjin	−97.7	−107.4	−135.3	−340.5	−61.4	−16.6	1.3	−76.8
	north	−227.1	324.7	334.8	432.3	−27.0	−46.8	−42.5	−116.2
	northeast	51.9	65.4	120.0	237.2	−9.0	−8.8	−8.1	−25.9
	southeast coast	94.6	−423.7	−800.0	−1129.0	−69.1	−41.6	11.3	−99.4
	central	166.2	20.5	134.0	320.8	−23.8	−16.3	−3.1	−43.2
	southwest	14.1	61.9	214.7	290.7	−49.2	−11.4	22.7	−37.9
	northwest	−2.0	58.7	131.8	188.5	−7.9	9.5	24.5	26.1

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