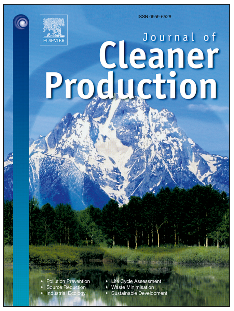

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[7850 Words]

Drivers of provincial SO_2 emissions in China – based on multi-regional input-output analysis

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Abstract: Studying the driving factors of pollutant emissions is of great significance for China in the formulation of pollution control strategies. Existing studies mainly focus on the causes of national aggregate emission changes. However, considering the large differences among provinces in China and their close economic linkages, it is necessary to develop a provincial-level analysis to shape provincial policies for emission reduction. Using the multi-regional input-output (MRIO) tables of 30 provinces in China and adopting structural decomposition analysis, we analyze how changes in the end-of-pipe treatment, cleaner production, economic production structure, domestic final use, domestic exports and international exports drive national and provincial SO_2 emissions. Decomposition results show that during 2002-2010 the absolute value of each effect based on the MRIO model is higher than that based on the national aggregate input-output model, which indicates that the existing studies adopting the national average data conceal the variation in the driving factors and underestimate their contributions to SO_2 emission changes. The decomposition results based on MRIO model further show that the end-of-pipe treatment and cleaner production are the major emission reduction factors for all provinces, and the effect of the former has noticeably increased during 2007-2010. For the eastern provinces, interestingly, the economic production structure becomes a major emission reduction factor during the period of 2007-2010. Changes in domestic final demand, domestic exports and international exports exhibit significantly different contributions among provinces. The increased final demand in eastern provinces largely drive SO_2 emissions for all provinces. Based on the above findings, policy implications that address the SO_2 emission reduction issues are proposed.

Key words: pollutant emission reduction; structural decomposition analysis; multi-regional input-output model; regional difference; China

1 Introduction

In the process of unprecedented economic growth, China is suffering severe air pollution. According to the latest China Environment Bulletin, of the 338 prefecture-level and above cities in China, 239 cities (70.7%) did not meet the required air quality standard in 2017 (MEE, 2018). Air pollution harms human health and affects economic sustainable development and social harmony. With the further growth of the economy and the increasing public demand for good air quality, China's pressure to control air pollution will continue to increase. How to achieve pollution reduction in the process of economic development has become a serious concern.

Chinese government has formulated a strict total emission reduction policy since the 11th Five-Year Plan. The 12th and 13th Five-Year Plan continues the practice of reducing the total emission of major pollutants, called the mandatory emissions control policy. It sets the emission reduction targets and assigns the task to provinces. The associated accomplishments directly affect the performance and promotion of heads of local governments. Therefore, it is important to identify the main driving forces of pollutant emissions growth for each province in China, so appropriate regional-specific emission reduction policies can be adopted. In this background, the present study aims to answer those questions: What are the main factors affecting the change of air pollutant emissions, and what is the contribution of each factor? Are there significant differences in the main contributors to air pollution control across provinces in China? This research will help to identify the pollution reduction routes for provinces in China and formulate reasonable and effective pollution control strategies.

The remainder of the article is structured as follows. Section 2 provides the literature review. Section 3 describes the method that quantifies the contributions of determinants to changes in pollutant emissions, the data sources and the manipulation techniques. Section 4 demonstrates the decomposition results in China and its 30 provinces and displays the central discussions. The conclusions are outlined in Section 5.

2 Literature Review

To control pollution, the driving forces of pollutant emissions must first be identified, which requires a systematic analysis of the internal connections between economic activities and pollutant emissions. An input-output (IO) model can adequately depict the linkage between intersectoral production technologies and final demand patterns, and the structural decomposition analysis (SDA) based on the IO model is a powerful tool to identify how various factors in an economy influence pollutant emissions (Hoekstra et al., 2002; Miller and Blair, 2009).

A number of scholars have examined the influencing factors of China’s energy consumption and carbon emissions using SDA approaches considering the wide attention given to the Kyoto Protocol and the national obligation to reduce carbon emissions (Peters et al., 2007; Guan et al., 2008; Minx et al., 2011; Zeng et al., 2014).

For example, Peters et al. (2007) and Guan et al. (2008) adopted the SDA approach to examine the effects of changes in technology, economic structure, urbanization, and lifestyles on CO_2 emissions in China for the periods of 1992–2002 and 2002–2005, respectively. Zeng et al. (2014) investigated the contributions of changes in sectoral energy efficiency, energy mix, production structure, and final demand category composition to changes in China's energy intensity during 1997–2007 using the SDA method.

As China's domestic air quality is seriously deteriorating, some scholars are concerned about the drivers of pollutant emissions. Guan et al. (2014) used SDA to study the changes in emissions of China's primary particulate matter, which is that smaller than 2.5 micrometers ($PM_{2.5}$), during the period of 1997−2010 and decomposed the changes into five driving forces: emission intensity, production structure, consumption structure, per capita consumption volume, and population. Liang et al. (2014) identified the underlying socioeconomic drivers of environmental pressure (including seven categories of resource flows and 24 types of waste flows) in China from 1992 to 2010 using the same decomposition method as that used by Guan et al. (2014). Zhang et al. (2015) identified the contributions of the end-of-pipe facilities and the phasing out of backward capacity to COD, NH_3-N, SO_2 and NOx emission reduction during the 11th Five-Year Plan (FYP) period in China. Liu and Wang (2017) examined the contributors responsible for the SO_2 and COD emission reductions during the 11th FYP period in China using the SDA approach.

However, most of the existing SDA studies in China have focused on national energy consumption, CO_2 emissions or pollutant emissions based on national aggregate IO tables. These studies provide scientific support for formulating energy or emission control policies at the national macro level without considering the differences among regions. In fact, China is a vast country with significant differences among regions in terms of income, industry structure, factor endowment, technology, and environmental regulations (Sueyoshi and Yuan, 2015; Zheng et al., 2019). In addition, province and province-level municipalities (hereafter referred to as the province) are the most important administrative units for formulating policies in China. Therefore, national aggregate analysis, which has low resolution, is not sufficient for adopting regional-specific emission control policies.

Some studies have carried out research in specific provinces and cities, but they either studied a single region or studied several regions using index decomposition analysis (IDA) model. For example, Geng et al. (2013), Wei et al. (2017) and Lei et al. (2018) studied the driving forces of energy-related CO_2 emissions in Liaoning, Beijing and Sichuan, respectively, using the single region SDA model. Feng et al. (2009) examined the contribution of lifestyle changes to CO_2 emissions changes in five provinces in China (Shanghai, Guangdong, Heilongjiang, Henan, and Gansu) during 1952-2002. Song and Zheng (2012) investigated the driving forces behind the changing energy intensities of 28 provinces during 1995-2009. Zhang et al. (2019) analyzed the socioeconomic factors of $PM_{2.5}$ concentrations in 152 Chinese cities.

Zheng et al. (2019) studied seven socioeconomic drivers of the changes in CO_2 emissions in China's 8 regions. But from Feng et al. (2009) to Zheng (2019), they all used the IDA model. Compared with SDA, IDA has a lower data requirement, which does not need the information of input-output tables. But this cause IDA lack refined decompositions of economic and technological effects and cannot examine the impacts of interdependencies of economic sectors on emissions. Hoekstra et al. (2003) offered a comprehensive comparison of the IDA and SDA approaches.

Several SDA studies at the regional and provincial levels provide more information than national aggregate SDA or provincial IDA, nevertheless they failed to consider the interregional economic linkages and could not reveal the true driving sources of pollutant emissions. For instance, Feng et al. (2012) used the 28 provincial IO tables of China and SDA to analyze the impacts of changes in population, technology, economic structure, consumption levels and patterns, and exports on provincial CO_2 emissions from 2002 to 2007. Zhao et al. (2012) used SDA to estimate the impacts of consumption patterns and technology on the carbon footprints of 8 regions in China and found that the pulling effect of consumption pattern change was stronger than the reducing effect of technological progress for most regions. Cao et al. (2019) used SDA to study the driving forces of carbon intensity changes in 30 provinces in China. However, it is noteworthy that close and complex economic linkages exist across different regions in China. According to Zhang (2013), between 1987 and 2007, the total amount of interprovincial trade in China increased by 29 times, with an average growth rate of 143% every 5 years. Moreover, a large portion of interprovincial trade has flowed into intermediate production processes (Feng et al., 2013; Liu and Wang, 2016). When these complex production linkages exist across regions, the multi-regional input-output (MRIO) model, rather than the regional input-output model, is highly needed. The MRIO model traces a complete production chain across regions and sectors, enables an understanding of the driving forces of emissions from the real final demand aspect, and thereby guides the formulation of pollution control policies.

Therefore, this article adopts the SDA method based on MRIO tables (MRIO-SDA) to examine the driving factors of pollution emissions changes in China and its provinces. As a result of the development of compilation techniques of multi-regional input-output tables over recent years, we can conduct research using the MRIO tables of 30 provinces in China to re-examine the driving factors of variations in pollutant emissions across China's provinces. To analyze the differences between the results obtained using the MRIO-SDA method and those using the conventional decomposition method based on national aggregate input-output tables (NIO-SDA), we also conducted a comparative analysis of these two methods and found some interesting results. In addition, existing decomposition studies focus on carbon emissions, while only limited attention has been paid to the emissions of air pollutants. Combined with the consideration of data availability, we chose SO_2, which is one of the key air pollutants controlled by the Chinese government and is one of the major components of fine particulate matter and haze (Yang et al., 2013), as the study objective to shed light on China's air pollution mitigation. This study also differs from existing studies in terms of influencing factors according to the characteristics of MRIO-SDA, such as separating intermediate inputs and final demand into local and external parts provincially. The research provides support for harmonizing regional emission reduction policies under the background of economic integration in China.

3 Methods and Data

3.1 Environmentally extended input–output analysis

An MRIO table with m regions and n sectors (m = 30 and n = 27 for China in this study) contains the following information: (1) z_{ij}^{rs}, the intermediate inputs from sector *i* in region *r* to sector *j* in region *s* (*r*, *s* = 1, 2… m; *i*, *j* = 1, 2… n); (2) y_i^{rs}, the final demand of region *s* for products in sector *i* from region *r*, and ex_i^r, the export of sector *i* in region *r*; and (3) x_i^r, the total output of sector *i* in region *r*.[1] For any sector *i* in region *r*, there is the following row balance:

$$x_i^r = \sum_j z_{ij}^{rr} + \sum_{s(s\neq r)} \sum_j z_{ij}^{rs} + y_i^{rr} + \sum_{s(s\neq r)} y_i^{rs} + ex_i^r \tag{1}$$

In other words, the total output of sector *i* in region *r* is partly used by region *r* itself for the intermediate inputs ($\sum_j z_{ij}^{rr}$) and final demand (y_i^{rr}), partly used by other regions for the intermediate inputs ($\sum_{s(s\neq r)} \sum_j z_{ij}^{rs}$) and final demand ($\sum_{s(s\neq r)} y_i^{rs}$), and partly used by other countries as exports (ex_i^r).

By defining $a_{ij}^{rs} = z_{ij}^{rs}/x_j^s$, Eq. (1) becomes

$$x_i^r = \sum_s \sum_j a_{ij}^{rs} x_j^s + \sum_s y_i^{rs} + ex_i^r \tag{2}$$

Further written in matrix form yields the following

$$\begin{bmatrix} X^1 \\ X^2 \\ \vdots \\ X^m \end{bmatrix} = \begin{bmatrix} \boldsymbol{A}^{11} & \boldsymbol{A}^{12} & \cdots & \boldsymbol{A}^{1m} \\ \boldsymbol{A}^{21} & \boldsymbol{A}^{22} & \cdots & \boldsymbol{A}^{2m} \\ \vdots & \vdots & \vdots & \vdots \\ \boldsymbol{A}^{m1} & \boldsymbol{A}^{m2} & \cdots & \boldsymbol{A}^{mm} \end{bmatrix} \begin{bmatrix} X^1 \\ X^2 \\ \vdots \\ X^m \end{bmatrix} + \begin{bmatrix} Y^{11} + Y^{12} + \cdots + Y^{1m} + Ex^1 \\ Y^{21} + Y^{22} + \cdots + Y^{2m} + Ex^2 \\ \vdots \\ Y^{m1} + Y^{m2} + \cdots + Y^{mm} + Ex^m \end{bmatrix} \tag{3}$$

The uppercase and bold uppercase font in this article represent the corresponding vectors and matrixes, respectively. Define $X = [X^1 \quad X^2 \quad \cdots \quad X^m]'$ as the $mn \times 1$ outputs vector in the MRIO model. Define $\boldsymbol{A} = [\boldsymbol{A}^{rs}]_{m\times m}$ as the $mn \times mn$ technical coefficient matrix. Similarly, $Y^s = [Y^{1s} \quad Y^{2s} \quad \cdots \quad Y^{ms}]'$ and $Ex = [Ex^1 \quad Ex^2 \quad \cdots \quad Ex^m]'$. Therefore, Eq. (3) changes to $X = \boldsymbol{A}X + \sum_s Y^s +$

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[1] The non-competitive import assumption is adopted for the MRIO table applied in this study. That is, the international imports item has been removed from domestic production and consumption in the MRIO table.

Ex. Solving for X yields

$$X = (\boldsymbol{I} - \boldsymbol{A})^{-1}(\textstyle\sum_s Y^s + Ex) \tag{4}$$

where $\boldsymbol{I}$ is the identity matrix. Define $\boldsymbol{L} = (\boldsymbol{I} - \boldsymbol{A})^{-1}$, which is known as the Leontief inverse matrix, of which the element l_{ij}^{rs} shows the total production of sector *i* in region *r* required to satisfy a particular final demand of sector *j* in region *s*.

Define D^r as the direct emission coefficient vector of region *r*. In other words, $D^r = (e_i^r / x_i^r)_{n\times 1}$, where e_i^r is the emission of sector i in region r. Let $D = [D^1 \quad D^2 \quad \cdots \quad D^m]'$, and then the pollutant emission vector *E*, which reflects the amount of emissions from each sector in each region, can be expressed as

$$E = \widehat{D}X = \widehat{D}\boldsymbol{L}(\textstyle\sum_s Y^s + Ex) \tag{5}$$

where $\widehat{D}$ represents the diagonal matrix of *D*.

3.2 Decomposition methodology

Changes in SO_2 emissions are decomposed using the MRIO-SDA approach to explore the driving forces behind these changes. Methodologically, there is no unique solution for decomposition (Dietzenbacher and Los, 1998; Ang and Zhang, 2000). When the number of factors is n, there are n! equivalent decomposition forms. Dietzenbacher and Los (1998) use the average of all n! equivalent decomposition forms to achieve an ideal decomposition. However, this method is cumbersome when the number of factors is large. Thus, the average of the two polar decompositions is proposed as an alternative method, and the value is remarkably close to the average of the full set of n! decompositions. Here, we adopted the widely used two-polar decomposition forms (Dietzenbacher and Los, 1998; Ang and Zhang, 2000). Based on Eq. (5), the emissions change between a base year (period 0) and a calculation year (period 1) is given by

$$\Delta E = E_1 - E_0 = \widehat{D}_1\boldsymbol{L}_1\left(\sum\nolimits_s Y_1^s + Ex_1\right) - \widehat{D}_0\boldsymbol{L}_0\left(\sum\nolimits_s Y_0^s + Ex_0\right)$$

$$= \frac{1}{2}\Delta\widehat{D}[\boldsymbol{L}_0(\textstyle\sum_s Y_0^s + Ex_0) + \boldsymbol{L}_1(\sum_s Y_1^s + Ex_1)] \tag{6.1}$$

$$+\frac{1}{2}\left[\widehat{D}_0\Delta\boldsymbol{L}(\textstyle\sum_s Y_1^s + Ex_1) + \widehat{D}_1\Delta\boldsymbol{L}(\sum_s Y_0^s + Ex_0)\right] \tag{6.2}$$

$$+\frac{1}{2}\textstyle\sum_s\left(\widehat{D}_0\boldsymbol{L}_0 + \widehat{D}_1\boldsymbol{L}_1\right)\Delta Y^s \tag{6.3}$$

$$+\frac{1}{2}\left(\widehat{D}_0\boldsymbol{L}_0 + \widehat{D}_1\boldsymbol{L}_1\right)\Delta Ex \tag{6.4}$$

where the subscript 1 indicates the calculation period, and the subscript 0 indicates the base period. ΔE represents the value difference between the calculation period and the base period. Similarly for $\Delta\widehat{D}$, $\Delta\boldsymbol{L}$, ΔY^s and ΔEx.

The four terms in Eq. (6) represent the contributions to emissions changes triggered by changes in emission intensity, economic production structure, domestic final demand and exports, respectively, while keeping the other variables constant. These four effects are labeled as D_{eff}, L_{eff}, Y_{eff}, and Ex_{eff}, respectively. The effect of domestic final demand Y_{eff} can be further decomposed into the effect of local final demand $Y_{\text{eff}}^{\text{d}}$ and the effect of domestic interregional exports $Y_{\text{eff}}^{\text{f}}$.

Changes in emission intensity are commonly viewed as advancements in environment-related technologies (Peters et al., 2007; Guan et al., 2008; Guan et al., 2014). Liu and Wang (2017) argue that the emission intensity factor can be further decomposed into factors of cleaner production and end-of-pipe treatment, which reflect different policy implications. According to Liu and Wang (2017), cleaner production is closely related to production technologies in economic activities which yield same output with less emissions, while end-of-pipe treatment depends on the investment in pollution treatment equipment (e.g., flue gas desulfurization equipment). For carbon emissions, the existing studies have not considered the factor of end-of-pipe treatment because extremely high costs can be incurred (e.g., carbon capture and storage technology). For pollutants such as SO_2, however, end-of-pipe treatment constitutes an important emissions-reduction approach, as indicated by China’s environmental protection experience during the 11th and 12th FYP periods. Therefore, in this article, the effect of cleaner production (measured by pollutant generation intensity) and the effect of end-of-pipe treatment (measured by pollutant emission rate) were examined separately.

Let $P = (p_i^r/x_i^r)_{mn\times 1}$ be the vector of pollutant generation intensity, where p_i^r denotes the pollutant amount generated in sector *i* of region *r*; $R = (e_i^r/p_i^r)_{mn\times 1}$ denotes the vector of the emission rate. There is $\widehat{D} = \widehat{R} \otimes \widehat{P}$, where $\otimes$ is a Hadamard product (element by element multiplication). Adopting the polar average decomposition method, $\Delta\widehat{D}$ can be further decomposed as

$$\Delta\widehat{D} = \frac{1}{2}\Delta\widehat{R} \otimes \left(\widehat{P}_0 + \widehat{P}_1\right) + \frac{1}{2}\left(\widehat{R}_0 + \widehat{R}_1\right) \otimes \Delta\widehat{P} \tag{7}$$

Substituting Eq. (7) into Eq. (6.1) derives the effect of end-of-pipe treatment R_{eff} and the effect of cleaner production P_{eff}:

$$R_{\text{eff}} = \frac{1}{4}\Delta\widehat{R} \otimes \left(\widehat{P}_0 + \widehat{P}_1\right)[\boldsymbol{L}_0(\textstyle\sum_s Y_0^s + Ex_0) + \boldsymbol{L}_1(\sum_s Y_1^s + Ex_1)] \tag{8}$$

$$P_{\text{eff}} = \frac{1}{4}\left(\widehat{R}_0 + \widehat{R}_1\right) \otimes \Delta\widehat{P}[\boldsymbol{L}_0(\textstyle\sum_s Y_0^s + Ex_0) + \boldsymbol{L}_1(\sum_s Y_1^s + Ex_1)] \tag{9}$$

Given $\boldsymbol{L} = (\boldsymbol{I} - \boldsymbol{A})^{-1}$, $\Delta\boldsymbol{L}$ can be further decomposed following the methods of Oosterhaven and van der Linden (1997) and Oosterhaven and Hoen (1998):

$$\Delta\boldsymbol{L} = \boldsymbol{L}_1 - \boldsymbol{L}_0 = \boldsymbol{L}_1 \Delta\boldsymbol{A}\boldsymbol{L}_0 \tag{10}$$

$\boldsymbol{A}$ contains four parts: $\boldsymbol{A}_*^{rr}, \boldsymbol{A}_*^{rs}, \boldsymbol{A}_*^{sr}$, and $\boldsymbol{A}_*^{-r\cdot}$, where $\boldsymbol{A}_*^{rr}$ is the matrix with all other elements being 0 except for the submatrix $\boldsymbol{A}^{rr}$, reflecting the structure of local intermediate inputs in region *r*; $\boldsymbol{A}_*^{rs}(r \neq s)$ is the matrix with all other elements being 0 except for $\boldsymbol{A}^{rs}$, reflecting the structure of intermediate inputs from region *r* to other regions; $\boldsymbol{A}_*^{sr}(r \neq s)$ is the matrix with all other elements being 0 except for $\boldsymbol{A}^{sr}$, reflecting the structure of intermediate inputs from other regions to region *r*; and $\boldsymbol{A}_*^{-r\cdot}$ is the matrix with all elements within $\boldsymbol{A}$ except for elements in submatrices $\boldsymbol{A}^{rr}$, $\boldsymbol{A}^{rs}$, and $\boldsymbol{A}^{sr}$ being 0, reflecting the intermediate inputs linkages among other regions outside the region *r*. Thus

$$\boldsymbol{A} = \boldsymbol{A}_*^{rr} + \boldsymbol{A}_*^{rs} + \boldsymbol{A}_*^{sr} + \boldsymbol{A}_*^{-r\cdot} \tag{11}$$

By substituting Eq. (11) into Eq. (10), the solution of which is then substituted into Eq. (6.2), the effects of the four factors on pollutant emissions can be derived, which are denoted by $A_{*\,\text{eff}}^{rr}$, $A_{*\,\text{eff}}^{rs}$, $A_{*\,\text{eff}}^{sr}$ and $A_{*\,\text{eff}}^{-r\cdot}$, respectively.

Table 1 summarizes the main abbreviations and symbols used in this article for quick reference.

Table 1 Description of the main abbreviations

Abbreviation	Description
SDA	Structural decomposition analysis
MRIO-SDA	SDA based on multi-regional input-output tables
NIO-SDA	SDA based on national aggregate input-output tables
R_{eff}	The effect of end-of-pipe treatment
P_{eff}	The effect of cleaner production
L_{eff}	The effect of economic production structure
Y_{eff}	The effect of domestic final demand
$Y_{\text{eff}}^{\text{d}}$	The effect of local final demand
$Y_{\text{eff}}^{\text{f}}$	The effect of domestic interregional exports
Ex_{eff}	The effect of exports
$A_{*\,\text{eff}}^{rr}$	The effect of structure of local intermediate inputs in region *r*
$A_{*\,\text{eff}}^{rs}$	The effect of the structure of intermediate inputs from region *r* to other regions
$A_{*\,\text{eff}}^{sr}$	The effect of structure of intermediate inputs from other regions to region *r*
$A_{*\,\text{eff}}^{-r\cdot}$	The effect of intermediate inputs linkages among other regions outside the region *r*

Notes: The effect of a factor means the contribution to emissions changes triggered by changes in this factor. For example, the effect of end-of-pipe treatment means the contribution to emissions changes triggered by changes in end-of-pipe treatment.

3.3 Data sources and manipulation

3.3.1 MRIO tables of China's 30 provinces

MRIO tables are compiled by scholars based on the provincial input–output tables (IOTs) for each of the 30 provinces (excluding Tibet, Hong Kong, Macau, and Taiwan) that are published by the National Statistical Bureau of China. Liu et al. (2012, 2014) estimated the trade flows among provinces using the well-known gravity model and compiled a 30-sector MRIO table of the 30 provinces in 2007 and in 2010. The results meet the desired requirement of our analysis and were adopted directly. More details about the original database and construction method of these Chinese MRIO tables can be found in Feng et al. (2013) and Liu et al. (2014). In terms of the MRIO in 2002, Li et al. (2010) extended provincial input-output tables by estimating the interprovincial trade flows using the gravity model, but they did not compile the 2002 China MRIO table. We constructed the 42-sector MRIO table of the 30 provinces for 2002 following the same compilation method as that used in Liu et al. (2012). Details about the compilation can be found in our previous work (Liu and Wang, 2015). To maintain consistency in sector classification, we aggregated the MRIO table (42 sectors in 2002 and 30 sectors in both 2007 and 2010) into 27 sectors. The detailed manipulation is shown in Table S1 in the Supplementary material. In addition, the 2007 and 2010 MRIO tables were transformed to the 2002 constant price to eliminate the impact of price change and to ensure data comparability among years.

3.3.2 Sectoral SO_2 emissions for 30 provinces

The sectoral SO_2 emissions data for each of the 30 provinces have not been officially published in current statistics. We estimate these values based on China's provincial energy consumption, which is a method that has been widely applied in previous SO_2 emissions inventory work (Streets et al., 2000; Zhang et al, 2009). Because coal combustion contributes 90% of the total SO_2 emissions in China (Zhang et al, 2009; Cao et al, 2011), the SO_2 emissions e is estimated as a product of coal consumption Q, sulfur content β and the removal rate of applied emission control devices η. Therefore, the SO_2 emission of sector i in region r (e_i^r) is calculated as $e_i^r = Q_i^r \times \beta_i^r \times (1 - \eta_i^r)$. More details about the estimation of SO_2 emissions can be seen in our previous work (Liu and Wang, 2015). To maintain consistency in sector classification, we aggregated the SO_2 emissions data (43 sectors estimated according to coal consumption) into 27 sectors. The detailed manipulation is shown in Table S1.

4 Results and discussion

4.1 Decomposition results of China's national aggregate SO_2 emission changes

Figure 1 presents the decomposition results of the national total SO_2 emission changes in China during the periods of 2002-2007 and 2007-2010 using the MRIO-SDA method. From 2002 to 2007, China's SO_2 emissions increased by 1084.5 thousand tons annually, while from 2007 to 2010, they decreased by 768.6 thousand tons annually. During both periods, end-of-pipe treatment and cleaner production were found to be the two major factors that reduced emissions, while economic production structure, domestic final demand, and international exports drive increases in emissions. By solely comparing the sign of each effect, the results of this study are consistent with those of Feng et al. (2012) and Liu and Wang (2017).

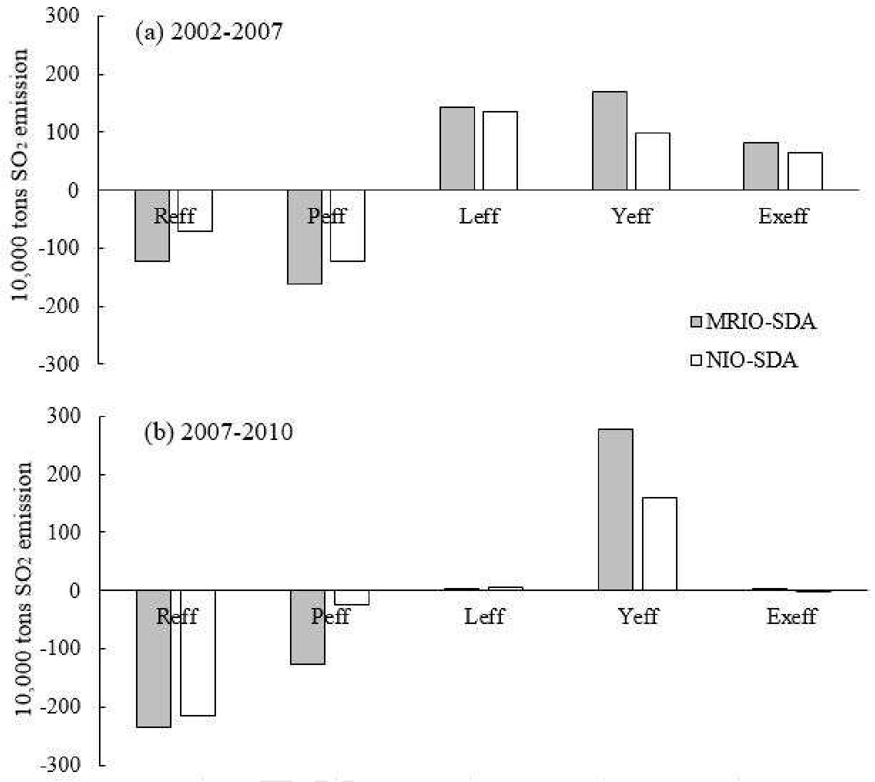

Figure 1 Decomposition results of changes in SO_2 emissions in China

Note: The decomposition results are reported by the annual average amount. Positive (negative) values denote that SO_2 emissions have been increased (decreased) due to the changes of factors.

Source: Calculated by the authors based on both MRIO-SDA and NIO-SDA methods.

We have also presented the decomposition results got from the NIO-SDA method to make better comparisons with existing studies. Figure 1 shows that the results obtained using the MRIO-SDA method are distinctly different from those obtained using the NIO-SDA method. Between 2002 and 2007, the five effects, whether they were related to an emission reduction or increase effect, invariably produced smaller values when using the NIO-SDA method than when using the MRIO-SDA method. In particular, the effect of end-of-pipe treatment obtained by using the NIO-SDA method amounted to only 58.37% of that obtained by using the MRIO-SDA method. For the effect of domestic final demand, 58.92%. During the period of 2007-2010, the results obtained through the two methods still exhibited distinct differences, which, however, were mainly clustered in the effects of cleaner production and domestic final demand. The effect of cleaner production accounted for only 9.58% of the total emission reduction effect under the NIO-SDA method and 35.20% under the MRIO-SDA method. Therefore, adopting national average emission intensity and production technologies results in the neglect of interregional differences, thus affecting the results of decomposition analysis to a large extent.

Further analysis found that SO_2 emission intensities across different provinces exhibited large differences. A Lorenz curve for SO_2 emissions has been drawn, where the cumulative proportion of economic output is represented by the horizontal axis, and the cumulative proportion of SO_2 emissions is represented by the vertical axis; the uneven distribution of emission intensities among regions is assessed by using the principle of the Gini coefficient (Cowell, 1995). Figure 2 presents the results of the four major sectors whose emissions accounted for 73.90% of the total emissions during the study period. In 2007, the Gini coefficients of SO_2 emissions in all four sectors, excluding the electricity sector, were higher than 0.4, which revealed considerable inequality. Moreover, most provinces were distributed in the right upper corner, which represents lower economic output and higher pollutant emissions. In addition, the Gini coefficient remained at a high value throughout the study period (Table S2). As noted by Lenzen (2011) and Su and Ang (2014), in the case of China, it is very necessary to use more detailed data to understand the driving forces of changes in pollutant emissions. Our research presents that the decomposition result of each effect obtained through the NIO-SDA method is relatively lower than that obtained through the MRIO-SDA method, indicating that the changes in the influencing factors can be concealed and their contributions to changes in SO_2 emissions may be underestimated when national average data are adopted.

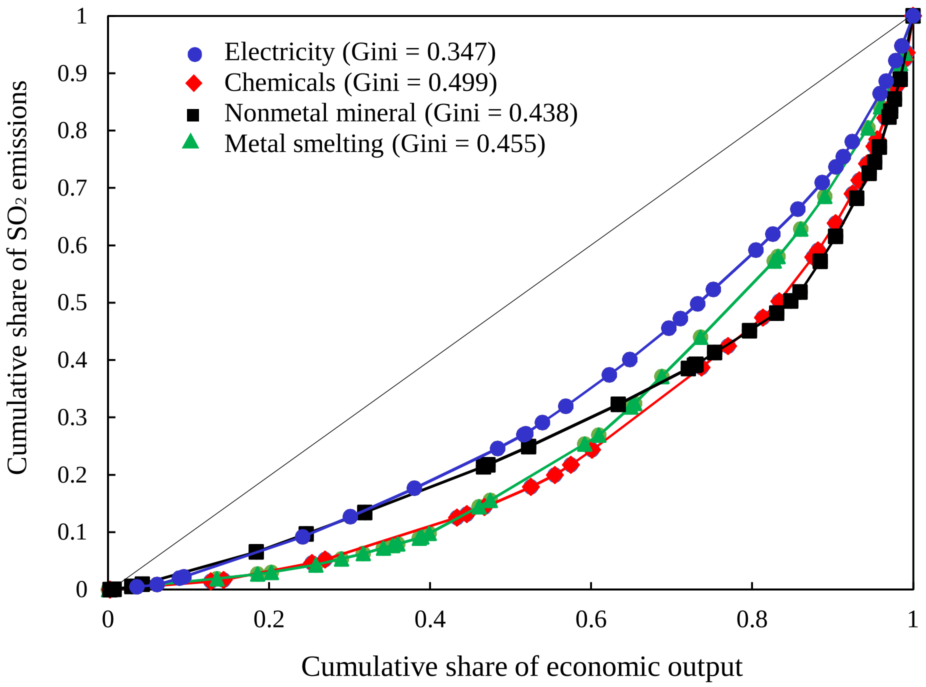

Figure 2 Environmental Gini coefficients of the four major sectors in 2007

Source: The environmental Gini coefficients are calculated by the authors based on the provincial GDP and SO_2 emissions data from the China Statistical Yearbook.

4.2 Decomposition results of regional SO_2 emissions changes

To better report our results and to have a general understanding of the results, we grouped 30 Chinese provinces into three regions – the eastern, central and western regions. The eastern region is the most developed region in China, while the western region is the least developed. Details of this grouping and the decomposition results are shown in Figure 3. During the period from 2002 to 2007, the SO_2 emissions increased in all three regions but decreased in 2007-2010, especially in the eastern region, which far exceeded the reduction range in the central and western regions.

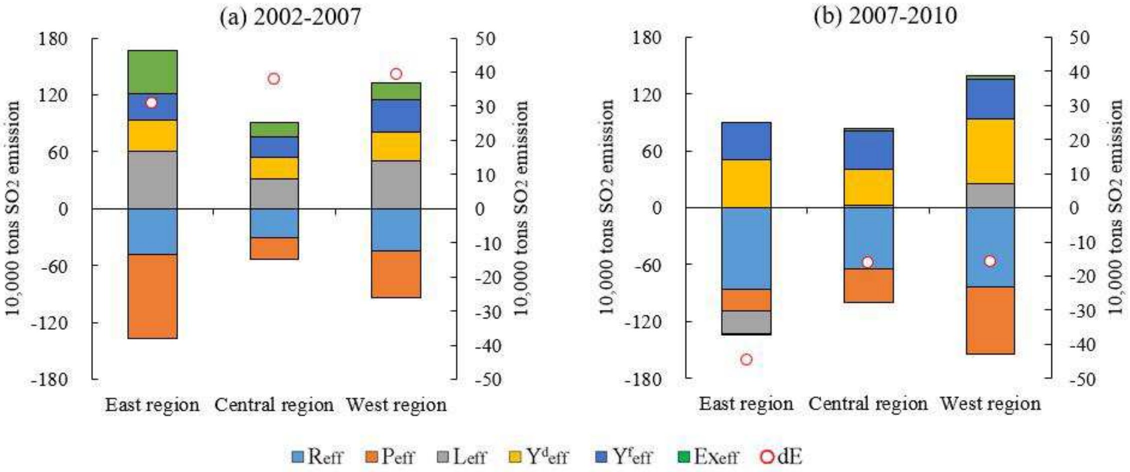

Figure 3 Decomposition results of regional SO_2 emission changes in 2002-2010

Notes: Decomposition results are reported by the annual average amount of SO_2 emissions. The secondary coordinate on the right is adopted for dE (emission changes). The region classification standard follows the China Statistical Yearbook, i.e., the eastern region includes Beijing, Tianjin, Hebei, Liaoning, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong and Hainan provinces. The central region includes Shanxi, Jilin, Heilongjiang, Anhui, Jiangxi, Henan, Hubei and Hunan provinces. The western region includes Guangxi, Inner Mongolia, Sichuan, Chongqing, Guizhou, Yunnan, Tibet, Shaanxi, Gansu, Qinghai, Ningxia and Xinjiang provinces.
Source: Calculated by the authors based on the MRIO-SDA method.

During the period of 2002-2007, the effect of cleaner production was the major reason for the emission reduction in the eastern region, which amounted to approximately 2 times the emission reduction effect of end-of-pipe treatment. In the central region, the treatment effect was the major reason for the emission reduction and amounted to 1.3 times the effect of that of cleaner production. In the western region, however, the effect of end-of-pipe treatment was roughly the same as that of cleaner production. In terms of the factors that increase SO_2 emissions, economic production structure was the major driver in all three regions. This result is consistent with the results of Zhang and Lahr (2014), who found that changes in production structure enhanced energy consumption in most regions in China from 2002 to 2007. This result may be related to the rapid development of China's industrialization, especially heavy industrialization. In terms of final demand[2], international exports was the major factor that increased emissions in the eastern region (accounting for 43.68% of the total effect of final demand); furthermore, local final demand was the major emission driver in the central region (accounting for 38.57% of the total effect of final demand), while domestic interregional exports was the major driver in the western region (accounting for 40.29% of the total effect of final demand).

During the period of 2007-2010, changes in end-of-pipe treatment became the most important contributor to the reduction of emissions in the eastern, central and western regions, which is consistent with the existing results obtained from studies focused on the national level. According to the assessment by the Chinese Academy for Environmental Planning, the end-of-pipe treatment in the electricity sector accounted for 69.27% of the total SO_2 emission reduction during the 11th FYP period (Wu et al., 2012). We also found that the effect of cleaner production had its contribution strengthened in the central and western regions during 2007-2010, which accounted for 34.57% and 46.01% of the total emission-reduction effect, respectively. Therefore, the results of Fig. 1, which show that the emission-reduction effect of cleaner production under the MRIO-SDA method is distinctly higher than that under the NIO-SDA method, may mainly be due to the contributions of cleaner production in the central and western regions. Thus, despite the strengthened investment in end-of-pipe treatment, the advancement of cleaner production technologies has yielded an eye-catching contribution to the reduction of SO_2 emissions in the central and western regions.

Interestingly, changes in the intermediate input technologies reduced the SO_2 emissions in the eastern region from 2007 to 2010, with a contribution rate that was comparable to the factor of cleaner production. That is, during the period of 2007-2010, the improvements of economic production structures in eastern provinces promoted reductions in the SO_2 emissions. This reduction was partly due to measures such as adjusting and upgrading the industrial structure, suppressing the secondary industry and developing the tertiary industry adopted in the most developed eastern provinces. Taking Guangdong province as an example, due to the increasing environmental pressure since 2007 and the decline in exports caused by the 2008 financial crisis, the traditional growth pattern of high resource consumption and high pollution emissions has been difficult to continue. Therefore, the Government of Guangdong province proposed a strategic decision of industry transfer, supporting the development of industries such as transportation, communications, and environmental protection, and supporting enterprises to expand their R&D and innovation capabilities (Government of Guangdong, 2008). These measures have promoted industrial upgrading and reduced pollution emissions.

As for the emission-increase effect, the local final demand has become a dominant contributor in the eastern and western regions, while the domestic interregional

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[2] For each region, final demand includes local final demand, domestic interregional exports and international exports.

exports and domestic final demand had equivalent contributions for the central region during the period of 2007-2010. According to Liu et al (2012, 2014), the central region is an extremely active region in inter-provincial trade. While undertaking industrial transfer from the eastern region, it supplies products for consumption in other regions, leading to domestic interregional exports as an important emission driver. The contribution of international exports has significantly declined, even to a negative value in the eastern region. This result is similar to Liu and Wang (2017) and Mi et al (2017), indicating the outbreak of the global financial crisis in 2008 impeded the exports and corresponding emissions of coastal areas in eastern China.

4.3 Decomposition results of SO_2 emission changes in different provinces

Figure 4 presents the decomposition results of the SO_2 emissions changes in the 30 provinces during the study period. From 2002 to 2007, most provinces increased their SO_2 emissions; however, during 2007-2010, all provinces except Qinghai and Xinjiang (two less developed provinces in the western region) had reduced emissions, showing a decoupling state in which SO_2 emissions decline as the economy grows. The contribution of each factor is different in the different provinces. A specific analysis of the contributions of these factors is provided below.

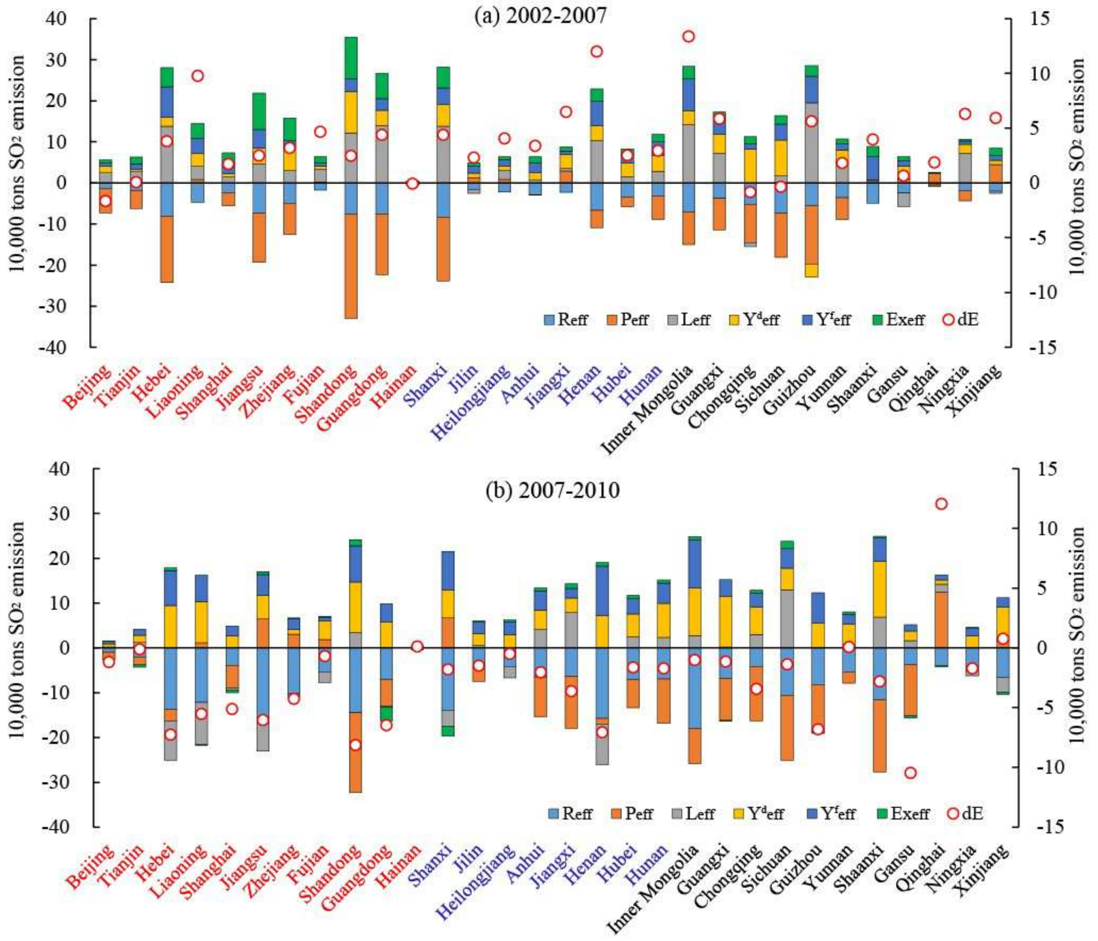

Figure 4 Decomposition results of SO_2 emission changes in different provinces during

2002-2010

Notes: The decomposition results are reported by the annual average amount of SO_2 emissions. The secondary coordinate on the right is adopted for dE (emission changes). The eastern, central and western provinces are marked in red, blue and black, respectively.
Source: Calculated by the authors based on the MRIO-SDA method.

(1) Major emission-reduction factors: end-of-pipe treatment and cleaner production

The effects of end-of-pipe treatment and cleaner production were basically negative for all provinces during the period of 2002-2007 (Fig. 4), and they both made important contributions to the reduction in SO_2 emissions. Moreover, the contribution of cleaner production was larger than that of end-of-pipe treatment in most provinces. This is because of measures such as eliminating small thermal power and small boilers adopted during this period. For example, from 2005 to 2007, a total of 3,120,500 kilowatts of small thermal power was shut down (National Energy Bureau, 2011). This enhanced production technology and largely reduced the SO_2 generated per unit output. Nevertheless, the emission reduction effect of end-of-pipe treatment in Hebei, Jiangsu, Shandong, Guangdong, Shanxi and Sichuan was noteworthy. These provinces were important energy and industrial production bases. Most companies in those provinces are traditional state-owned enterprises, which led them to conduct centralized abatement of SO_2 emissions at an early stage.

During the period of 2007-2010, the effects of end-of-pipe treatment and cleaner production were still negative across provinces, resulting in a continuous reduced emission contribution. In addition, the contribution of end-of-pipe treatment was significantly enhanced, especially for the eastern provinces. In many central and western provinces (such as Anhui, Jiangxi, Shaanxi, Gansu), cleaner production remained the major emission-reduction factor. This result reflects that the competence of end-of-pipe treatment was limited in less developed provinces, and their SO_2 emission reductions were mainly achieved through gradual improvements in production processes. According to Li et al (2012), in 2009, investment in pollution treatment in developed provinces all exceeded 20 billion yuan, while in developing provinces it was far below the national average.

The sectoral distribution of these two emission-reduction factors across provinces is further studied. The top three sectors are electricity, nonmetal mineral products, and metal smelting and pressing (Table 2). Based on the average level across the 30 provinces, the electricity sector accounted for 82.62% and 85.76% of the total emission reduction effect of end-of-pipe treatment in 2002-2007 and in 2007-2010, respectively. The electricity also occupied a dominant position in the effect of cleaner production. This result is attributable to the substantially increased efforts in pollution treatment in the electricity sector in China, such as adopting electricity price subsidies for desulfurization by provinces and encouraging the installation and operation of end-of-pipe treatment facilities. Research has shown that for thermal power plants which contribute almost 60% of SO_2 emissions, the proportion of flue gas desulfurization power units in all power units increased from 48% in 2007 to 82.6% in 2010 (Wang and Jiang, 2012).

Table 2 Major sectors of the effect of end-of-pipe treatment and cleaner production on SO_2 emissions in different provinces

	Reff (2002-2007)			Peff (2002-2007)			Reff (2007-2010)			Peff (2007-2010)		
	S22	S13	S14	S22	S13	S14	S22	S13	S14	S22	S13	S14
Beijing	-96.31	-1.54	-0.69	-84.97	-4.34	-1.38	-86.44	0.01	-0.56	-1.36	-20.49	-8.48
Tianjin	-92.75	-0.58	-0.53	-68.38	0.01	0.07	-82.25	0.01	-8.00	-321.31	1.00	199.17
Hebei	-84.09	-1.98	-1.11	-93.43	2.21	-1.67	-91.59	0.01	-1.81	495.79	-105.44	-41.28
Liaoning	-88.00	-1.76	-2.34	-246.50	145.78	40.97	-91.21	0.01	-3.17	1184.70	-416.64	89.61
Shanghai	-84.75	-0.52	-1.44	-163.20	4.80	17.56	-81.24	0.00	-2.15	57.68	-8.65	-23.64
Jiangsu	-94.44	-1.66	-0.36	-76.44	-0.73	-2.44	-91.52	0.01	-0.43	219.05	-50.46	5.68
Zhejiang	-95.17	-2.30	-0.17	-83.03	-9.71	-0.04	-93.88	0.01	-0.27	241.86	-66.53	4.32
Fujian	-92.20	-4.05	-0.16	-70.64	5.96	6.25	-92.92	0.01	-0.31	238.89	-83.49	10.12
Shandong	-78.84	-4.05	-1.58	-62.51	-16.48	-0.04	-77.65	0.01	-2.28	83.28	-41.79	-10.22
Guangdong	-93.71	-2.93	-0.31	-81.86	-2.69	-2.75	-75.62	0.02	-12.04	-299.45	-135.20	366.37
Hainan	-95.01	-3.26	-0.02	-65.75	-8.42	-0.09	-99.15	0.01	-0.02	162.12	-87.93	0.18
Shanxi	-46.96	-0.80	-0.97	-33.87	-2.68	-4.43	-79.94	0.00	-1.91	171.69	-15.75	32.62
Jilin	-92.66	-3.08	-0.15	-10.82	111.02	1.37	-91.29	0.01	-0.23	49.35	-40.04	0.84
Heilongjiang	-90.99	-0.72	-0.24	-61.53	17.87	8.56	-73.44	0.00	-1.50	-8744.24	-886.96	2370.81
Anhui	-89.51	-3.28	-0.36	-3199.92	2149.75	-64.48	-93.84	0.02	-0.48	42.46	-85.23	2.03
Jiangxi	-82.70	-4.12	-0.49	38.86	55.16	-3.05	-97.19	0.02	-0.78	-4.86	-38.51	0.93
Henan	-83.94	-2.00	-0.89	-80.39	8.16	-16.47	-88.27	0.01	-1.54	914.53	-388.23	237.67
Hubei	-85.18	-2.02	-0.36	-153.58	17.17	3.84	-84.68	0.01	-0.91	-8.30	-27.57	5.58
Hunan	-77.62	-4.72	-2.22	-43.69	7.38	-16.73	-78.28	0.02	-3.01	15.36	-65.05	16.50
Inner Mongolia	-89.12	-0.72	-0.95	-66.30	2.95	-8.10	-95.29	0.00	-1.35	65.15	-22.61	11.71
Guangxi	-83.94	-7.76	-3.56	-97.84	31.12	-31.63	-80.97	0.04	-4.69	31.09	-93.06	10.92
Chongqing	-82.04	-3.28	-0.18	-73.82	-2.40	0.64	-75.41	0.03	-11.13	-88.72	-77.97	94.68
Sichuan	-61.65	-2.79	-0.86	-36.75	16.81	-4.55	-81.50	0.02	-1.11	-1.90	-59.23	-8.10
Guizhou	-56.22	-0.97	-0.82	-97.50	-13.28	4.00	-78.05	0.00	-1.56	187.71	10.08	-15.32
Yunnan	-45.06	-1.90	-0.44	-20.20	21.09	-4.34	-84.58	0.01	-0.83	154.57	-80.99	14.65
Shaanxi	-86.80	-2.59	-0.13	-2825.31	2967.94	-92.19	-90.60	0.01	-0.68	-49.44	-27.51	10.31
Gansu	-90.42	-2.62	-1.52	127.02	6.50	-7.53	-66.41	0.01	-1.88	-73.51	-9.93	-10.94
Qinghai	-68.48	-0.59	-1.13	-14.85	-2.77	4.43	-88.38	0.00	-2.78	86.21	8.32	18.01
Ningxia	-88.88	-0.91	-0.09	-94.45	4.76	0.17	-95.02	0.00	-0.15	164.67	-95.89	-0.50
Xinjiang	-81.13	-2.70	-0.79	62.42	17.49	-0.38	-86.08	0.01	-1.76	173.26	-84.53	125.69

Note: S22, S13 and S14 denote the sectors of electricity, nonmetal mineral products, and metal smelting and pressing, respectively. The results are provided in percentages. For each province, the numeric value denotes the proportion of a certain sector to the total emission reduction effect of a certain factor. A negative value represents the effect of an emission reduction and vice versa.

Source: Calculated by the authors based on the MRIO-SDA method.

Additionally, despite the large emission-reduction effects of end-of-pipe treatment and cleaner production, the pollution emissions intensity was still high in some provinces. Figure 5 shows the provincial SO_2 emission coefficients in the electricity sector. In total, SO_2 emission intensities were substantially reduced from 2002 to 2010. However, the intensities in the provinces of Shaanxi, Sichuan, Shanxi, Inner Mongolia and Guizhou were higher than the national average and far exceeded those of developed provinces, such as Beijing, Shanghai and Guangdong, by 2010. Thus, compared to developed provinces, the emission intensities in the provinces of Shaanxi, Sichuan, Shanxi, Inner Mongolia and Guizhou still have the potential to be alleviated (Zheng et al., 2019). As such, emission reduction technologies should be accelerated in those provinces; in the medium- to long-term, measures such as optimizing the energy structure and reducing the consumption portion of coal while elevating that of renewable energy are undoubtedly important.

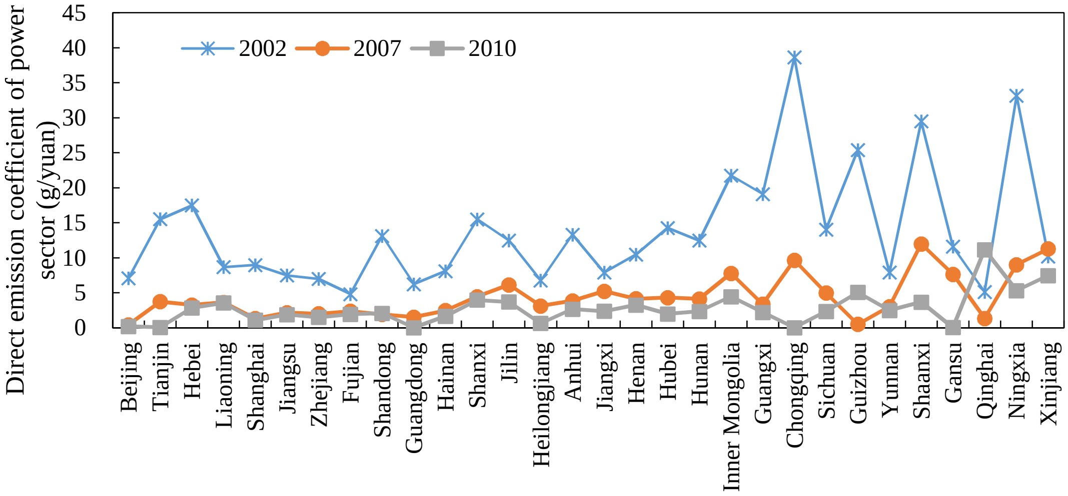

Figure 5 SO_2 emission intensities in the electricity sector in different provinces

Source: Calculated by the authors based on SO_2 emissions and output data from the electricity sector of each province.

(2) The emission effect of economic production structure

As indicated in Figure 4, the effect of economic production structure exhibited positive values in most provinces during the period of 2002-2007, which means that the changes in the intermediate input structure increased the SO_2 emissions. In particular, in the provinces of Hebei, Shandong, Guangdong, Shanxi, Henan, Inner Mongolia and Guizhou, the emission increase effect of economic production structure was quite large, even became the leading driver. These provinces mainly focus on industries with large energy consumption and mass pollution emissions, such as electricity, steel, cement, and chemicals (National Bureau of Statistics, 2008). As the industrial structure further focus on heavy industry, SO_2 emissions increase. However, during 2007-2010, the emission effect of economic production structure decreased, especially in the eastern provinces of Hebei, Liaoning, Jiangsu and Fujian, where an emission reduction effect was presented. This result indicates that the economic production structure shifted toward a low-emission direction during 2007-2010 in the developed eastern provinces.

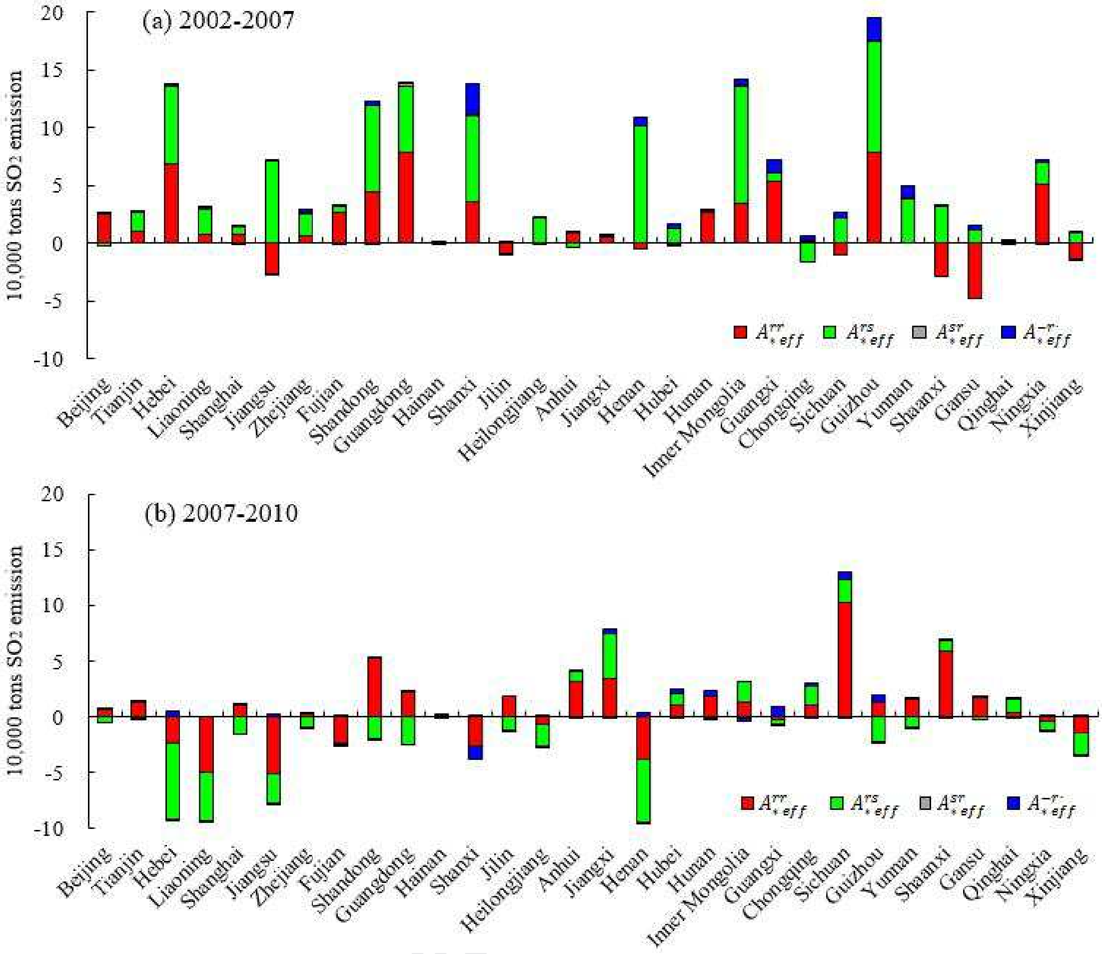

Figure 6 Further decomposition results of the effect of economic production structure

Note: The decomposition results are reported by the annual average amount of SO_2 emissions. *Source*: Calculated by the authors based on the MRIO-SDA method.

The effect of the economic production structure (L_{eff}) is further decomposed into four parts, $A_{*\,\text{eff}}^{rr}$, $A_{*\,\text{eff}}^{rs}$, $A_{*\,\text{eff}}^{sr}$ and $A_{*\,\text{eff}}^{-r\cdot}$, as shown in Figure 6. The results indicate that $A_{*\,\text{eff}}^{rr}$ and $A_{*\,\text{eff}}^{rs}$ were the major contributors. During the period of 2002-2007, the $A_{*\,\text{eff}}^{rs}$ values in the provinces of Jiangsu, Shandong, Shanxi, Henan, Inner Mongolia and Guizhou were even higher than the values of $A_{*\,\text{eff}}^{rr}$, which implied that changes in the intermediate inputs to other provinces have significantly increased their SO_2 emissions. This result is attributable to their resource endowments, which maintained the supply of pollution-intensive intermediate products, such as electricity and steel products. In 2007-2010, however, the emission effect of the intermediate input structure significantly dropped, even declining to negative values in Hebei, Liaoning, Jiangsu and Henan as an emission reduction effect. The major contribution came from $A_{*\,\text{eff}}^{rr}$ in Liaoning and Jiangsu. In other words, the improvement of the local production technologies reduced their local SO_2 emissions. In Hebei and Henan, emission reduction mainly depended on the contribution of $A_{*\,\text{eff}}^{rs}$, showing that their emissions were reduced because of the changes in the intermediate input to other provinces. As they are major emission provinces adjacent to the capital city Beijing, in order to improve Beijing’s air quality, they actively implemented policies including promoting circular economy and reducing pollution-intensive production (Zheng et al., 2019).

Overall, the change in the economic production structure in China decreased the SO_2 emissions during the study period. However, in the provinces of Shandong, Jiangxi, Sichuan and Shaanxi, the emissions still exhibited an increasing trend, for which $A^{rr}_{*\,\mathrm{eff}}$ was the major contributor. This result indicates that during the period, a “high pollution” trend still dominated the intermediate input structures in those provinces; thus, measures such as improving production technologies and adjusting industrial structures are urgently needed.

(3) The emission effect of final demand

The emission effect of final demand is composed of the effect of domestic final demand, domestic exports and international exports. As shown in Figure 3, the effects basically exhibited positive values during the study period, increasing SO_2 emissions. For eastern provinces, the emission effect of international exports was extremely high during the period of 2002-2007, and far surpassed that in the central and western provinces; however, it significantly declined during the period of 2007-2010, even to negative values in some provinces (such as Tianjin, Shanghai and Guangdong). This is largely related to the financial crisis (Mi et al., 2017). The emission increase effects of the domestic final demand and domestic exports were almost equal in most provinces, reflecting that provincial SO_2 emissions were not only subject to the local final demand but also influenced by the final demand from other provinces.

Figure 7 presents the regional distribution of the effect of domestic exports in each province. During the period of 2002-2007, the effect of domestic exports in either the eastern, central, or western regions was invariably concentrated in the eastern provinces (especially Tianjin, Shanghai, Zhejiang and Guangdong). This result reflects that the increasing final demand in the eastern provinces drove the SO_2 emissions in most provinces. During the period of 2007-2010 (Figure 8), the effect of domestic exports in each province was still concentrated in the eastern provinces, particularly in provinces with intensive manufacturing industries such as Hebei, Jiangsu and Shandong. Therefore, although China’s exports had dramatically declined in 2007-2010 due to the 2008 financial crisis, the increasing domestic demand in eastern China became a major cause driving SO_2 emissions. This is similar to the results of Liu and Wang (2016)._Moreover, the increasing final demand in some central and western provinces (such as Jilin, Henan, Inner Mongolia, and Shaanxi) also became major contributors to SO_2 emissions. That is, with the economic development of the central and western provinces, their growing consumption increased SO_2 emissions in other provinces.

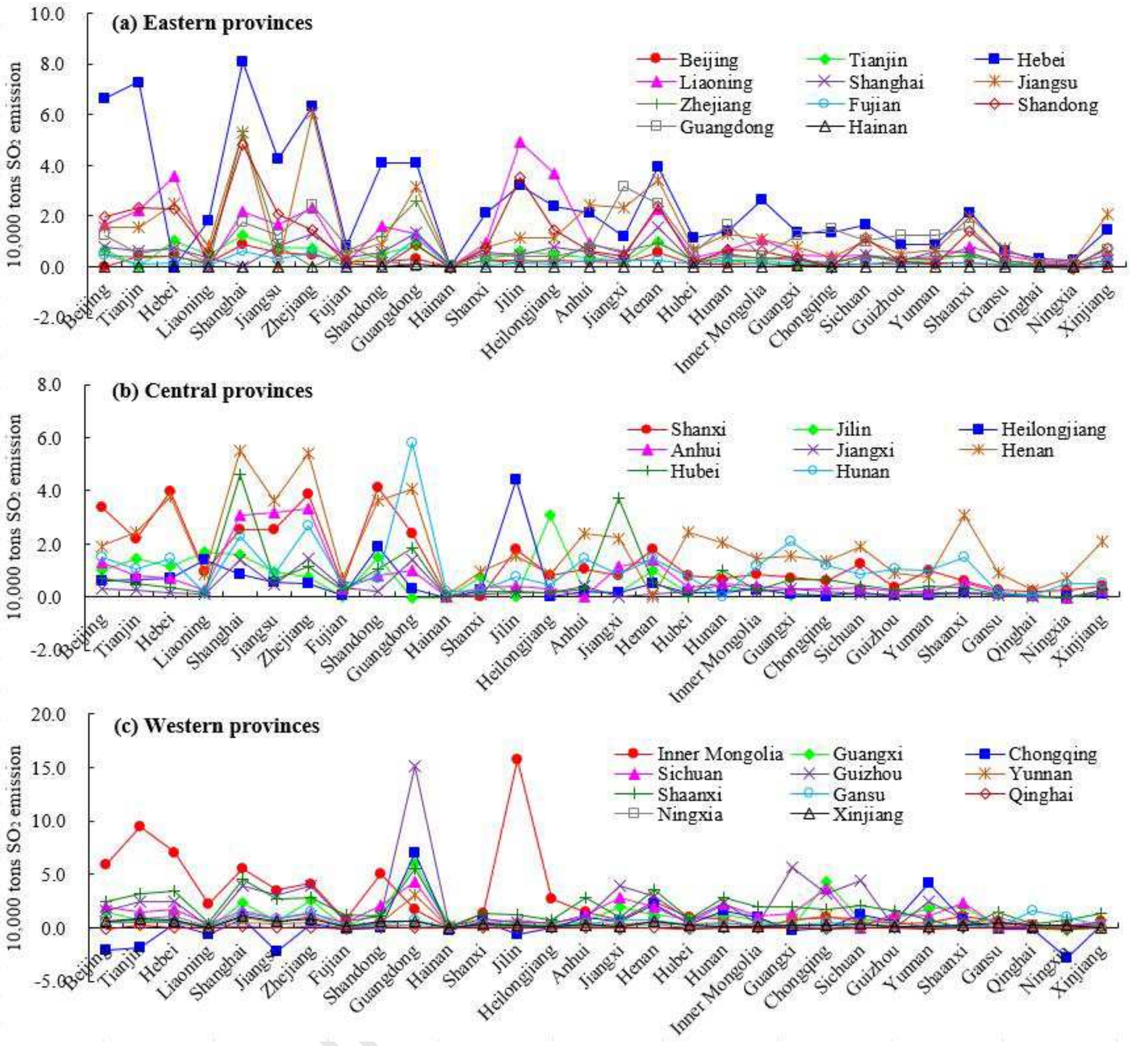

Figure 7 Regional sources of the effect of domestic exports in different provinces during 2002-2007

Note: The results are reported by the annual average amount of SO_2 emissions. Taking Hebei province in figure (a) for example, the blue line presents the contribution of demand change in each province (except for Hebei) on SO_2 emission change in Hebei. Result shows that demand in Beijing, Tianjin, Shanghai, Zhejiang, Shandong and Guangdong are the major contributor to the effect of domestic exports in Hebei.

Source: Calculated by the authors based on the MRIO-SDA method.

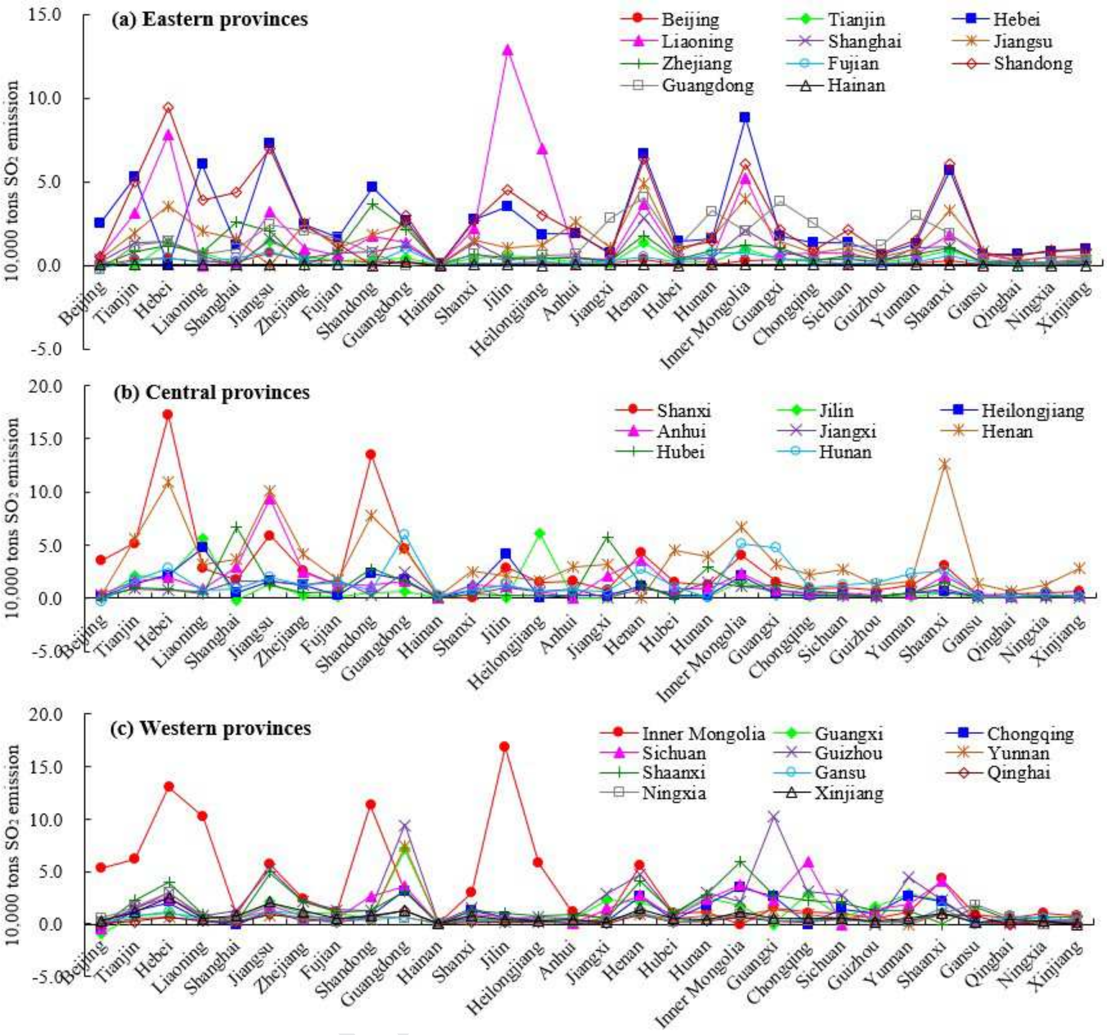

Figure 8 Regional sources of the effect of domestic exports in different provinces during 2007-2010

Note: The results are reported by the annual average amount of SO_2 emissions.
Source: Calculated by the authors based on the MRIO-SDA method.

4.4 Policy implications

The analysis using the SDA method presents the results of the study period, and strictly speaking, it cannot be used to forecast the future. However, the weaknesses in the past may well be the points that require attention and corrections in the future. Thus, we propose the following policy implications with respect to the reduction of the SO_2 emissions in China based on the results of our study.

From the perspective of production, first, regional differences should be considered when formulating emission reduction policies, as indicated by the result differences between the MRIO-SDA and NIO-SDA methods. For example, although end-of-pipe treatment has been the main factor that reduced SO_2 emissions, there is still potential for the central and western provinces to improve treatment capacity. In particular, provinces such as Shaanxi, Inner Mongolia and Guizhou still need to strengthen their efforts regarding end-of-pipe treatment to reduce SO_2 emissions, especially in the sectors of electricity, nonmetallic mineral products, and metal smelting and pressing. Second, more attention needs to be focused on the role of cleaner production. During the study period, cleaner production played an important role in SO_2 emission reduction; however, this factor is frequently neglected in existing studies. Meanwhile, considering the relatively backward production technology in the central and western provinces as well as their support for the production of developed eastern provinces, enhanced support in terms of funding and technologies for cleaner production should be provided to the central and western provinces. Third, it is necessary to continue optimizing the economic production structure. Although the economic structure adjustment might be slow and closely related to the stages of economic development, it had already exhibited an emission reduction effect in the eastern region during 2007-2010. Nevertheless, during the process of optimizing and adjusting economic structures, regional economic linkages should be emphasized to avoid the shift of pollution across regions. Efforts should be strengthened to supervise the structural emission reduction measures taking place in the eastern region; specifically, the high pollution-intensive industries should receive particular supervision to prevent the shift of pollution towards the central and western regions.

From the perspective of consumption, attention should be paid to the driving force of final demand on SO_2 emissions in China. First, provide guidance on rational and green consumption, especially for the eastern provinces of which the domestic final demand predominantly drives SO_2 emissions. Second, considering that China is now in a transitional period where “growth is driven by the increase of domestic demand”, it is necessary to reconcile the contradiction between “consumption expansion” and “pollution emission reduction” for sustainable development. A responsibility model that holds consumers accountable for pollutant emissions can be explored in the future to advocate green consumption. Third, the structure of international exports should be further optimized to improve the pollution terms of exports. Opening-up oriented policies, such as the Belt and Road initiative, should be drawn upon to optimize the allocation of factors, including environmental resources, in the international market.

5 Conclusion

Studying the driving factors of SO_2 emissions is of great significance for the formation of China’s pollution control strategies. As the largest developing country in the world, China is characterized by considerable differences among its provinces in terms of economic development and pollution control. The existing studies have mainly focused on the drivers of the national aggregate SO_2 emission changes and thus cannot provide targeted guidance on emission control policies for specific provinces. A few studies have analyzed the determinants of pollution emissions at the provincial level but have neglected the complex interprovincial economic linkages. By adopting the structural decomposition analysis based on the MRIO method, this research considered both the interprovincial and the intersectoral production linkages and analyzed the driving factors and their contributions to the changes in SO_2

emissions in China’s provinces. The research has found the following:

(i) The results obtained using the MRIO-SDA method were higher than those obtained using the traditional NIO-SDA method. During the period of 2002-2007, the effects of end-of-pipe treatment and domestic final demand under the NIO-SDA method account for only 58.37% and 58.92%, respectively, of those under the MRIO-SDA method. During the period of 2007-2010, the results obtained through the two methods still exhibited distinct differences, which, however, were mainly clustered in the effects of cleaner production and domestic final demand. This result indicates that the analysis based on national average data conceals and underestimates the contributions of the influencing factors of SO_2 emissions.

(ii) The results obtained using the MRIO-SDA method indicate that end-of-pipe treatment and cleaner production were major emission reduction factors in China and its provinces, and the effect of end-of-pipe treatment was distinctly enhanced, becoming the predominant emission reduction factor in all provinces during 2007-2010. The intermediate input technology appeared to be an emission increasing factor; however, during 2007-2010, it became an important emission reduction factor for the eastern region, which had almost the same emission effect as the factor of cleaner production. This result indicates that the economic production structures in the eastern provinces transitioned in a cleaner direction and helped reduce SO_2 emissions. The domestic final demand, domestic exports and international exports served as the main pollution increasing factors, but they had varied contributions among the different provinces. During 2007-2010, the effect of international exports significantly declined due to the impact of the global financial crisis, and it even dropped to negative values in some eastern provinces. The effect of domestic exports acted as a driving factor of increasing SO_2 emissions, which was comparable to the effect of domestic final demand. The regional distribution of the effect of domestic exports indicates that the final demand of the eastern provinces was the major cause driving SO_2 emissions in all provinces.

The results based on the MRIO-SDA method are helpful for formulating detailed and targeted emission reduction policies because they reveal the driving forces of SO_2 emissions at the provincial level. However, due to data availability constraints, in this study, we covered only the period of 2002-2010. In fact, since 2011, China's pollution emission statistics methods and calibrations have been revised by the Ministry of Ecology and Environment (MEE). According to the MEE, the statistical scope of SO_2 emissions expand from industrial sources and urban living sources to agricultural sources, automotive vehicle sources and centralized pollution abatement sources. In addition, the SO_2 removal data were no longer collected starting in 2011, making it impossible to distinguish the contributions of end-of-pipe treatment and cleaner production. Therefore, although the 2012 MRIO table has been published by Mi et al. (2017) and Liu et al. (2018), this study did not extend the research period to 2012. Actually, a study based on the period of 2002-2010 is sufficient to reveal the differences between the two methods, MRIO-SDA and NIO-SDA, and the differences in the emission drivers between provinces. But the research conclusions and policy implications drawn from this paper must be used with caution. In the future, the study can be expanded to cover the latest periods and different pollutants with updated data. For example, studying NOx simultaneously to compare the results including interlinks between SO_2 and NOx.

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Table 2 Major sectors of the effect of end-of-pipe treatment and cleaner production on SO_2 emissions in different provinces

	R_{eff} (2002-2007)			P_{eff} (2002-2007)			R_{eff} (2007-2010)			P_{eff} (2007-2010)		
	S22	S13	S14	S22	S13	S14	S22	S13	S14	S22	S13	S14
Beijing	-96.31	-1.54	-0.69	-84.97	-4.34	-1.38	-86.44	0.01	-0.56	-1.36	-20.49	-8.48
Tianjin	-92.75	-0.58	-0.53	-68.38	0.01	0.07	-82.25	0.01	-8.00	-321.31	1.00	199.17
Hebei	-84.09	-1.98	-1.11	-93.43	2.21	-1.67	-91.59	0.01	-1.81	495.79	-105.44	-41.28
Liaoning	-88.00	-1.76	-2.34	-246.50	145.78	40.97	-91.21	0.01	-3.17	1184.70	-416.64	89.61
Shanghai	-84.75	-0.52	-1.44	-163.20	4.80	17.56	-81.24	0.00	-2.15	57.68	-8.65	-23.64
Jiangsu	-94.44	-1.66	-0.36	-76.44	-0.73	-2.44	-91.52	0.01	-0.43	219.05	-50.46	5.68
Zhejiang	-95.17	-2.30	-0.17	-83.03	-9.71	-0.04	-93.88	0.01	-0.27	241.86	-66.53	4.32
Fujian	-92.20	-4.05	-0.16	-70.64	5.96	6.25	-92.92	0.01	-0.31	238.89	-83.49	10.12
Shandong	-78.84	-4.05	-1.58	-62.51	-16.48	-0.04	-77.65	0.01	-2.28	83.28	-41.79	-10.22
Guangdong	-93.71	-2.93	-0.31	-81.86	-2.69	-2.75	-75.62	0.02	-12.04	-299.45	-135.20	366.37
Hainan	-95.01	-3.26	-0.02	-65.75	-8.42	-0.09	-99.15	0.01	-0.02	162.12	-87.93	0.18
Shanxi	-46.96	-0.80	-0.97	-33.87	-2.68	-4.43	-79.94	0.00	-1.91	171.69	-15.75	32.62
Jilin	-92.66	-3.08	-0.15	-10.82	111.02	1.37	-91.29	0.01	-0.23	49.35	-40.04	0.84
Heilongjiang	-90.99	-0.72	-0.24	-61.53	17.87	8.56	-73.44	0.00	-1.50	-8744.24	-886.96	2370.81
Anhui	-89.51	-3.28	-0.36	-3199.92	2149.75	-64.48	-93.84	0.02	-0.48	42.46	-85.23	2.03
Jiangxi	-82.70	-4.12	-0.49	38.86	55.16	-3.05	-97.19	0.02	-0.78	-4.86	-38.51	0.93
Henan	-83.94	-2.00	-0.89	-80.39	8.16	-16.47	-88.27	0.01	-1.54	914.53	-388.23	237.67
Hubei	-85.18	-2.02	-0.36	-153.58	17.17	3.84	-84.68	0.01	-0.91	-8.30	-27.57	5.58
Hunan	-77.62	-4.72	-2.22	-43.69	7.38	-16.73	-78.28	0.02	-3.01	15.36	-65.05	16.50
Inner Mongolia	-89.12	-0.72	-0.95	-66.30	2.95	-8.10	-95.29	0.00	-1.35	65.15	-22.61	11.71
Guangxi	-83.94	-7.76	-3.56	-97.84	31.12	-31.63	-80.97	0.04	-4.69	31.09	-93.06	10.92
Chongqing	-82.04	-3.28	-0.18	-73.82	-2.40	0.64	-75.41	0.03	-11.13	-88.72	-77.97	94.68

Sichuan	-61.65	-2.79	-0.86	-36.75	16.81	-4.55	-81.50	0.02	-1.11	-1.90	-59.23	-8.10
Guizhou	-56.22	-0.97	-0.82	-97.50	-13.28	4.00	-78.05	0.00	-1.56	187.71	10.08	-15.32
Yunnan	-45.06	-1.90	-0.44	-20.20	21.09	-4.34	-84.58	0.01	-0.83	154.57	-80.99	14.65
Shaanxi	-86.80	-2.59	-0.13	-2825.31	2967.94	-92.19	-90.60	0.01	-0.68	-49.44	-27.51	10.31
Gansu	-90.42	-2.62	-1.52	127.02	6.50	-7.53	-66.41	0.01	-1.88	-73.51	-9.93	-10.94
Qinghai	-68.48	-0.59	-1.13	-14.85	-2.77	4.43	-88.38	0.00	-2.78	86.21	8.32	18.01
Ningxia	-88.88	-0.91	-0.09	-94.45	4.76	0.17	-95.02	0.00	-0.15	164.67	-95.89	-0.50
Xinjiang	-81.13	-2.70	-0.79	62.42	17.49	-0.38	-86.08	0.01	-1.76	173.26	-84.53	125.69

Note: S22, S13 and S14 denote the sectors of electricity, nonmetal mineral products, and metal smelting and pressing, respectively. The results are provided in percentages. For each province, the numeric value denotes the proportion of a certain sector to the total emission reduction effect of a certain factor. A negative value represents the effect of an emission reduction and vice versa.

Source: Calculated by the authors based on the MRIO-SDA method.

Highlights

► Drivers of provincial SO_2 emissions in China is examined by using MRIO-SDA.

► Large differences and close economic linkages among provinces in China are captured.

► Absolute value of decomposition results based on the MRIO model were higher than that based on the national aggregate IO model.

► Changes of economic production structures reduced SO_2 emissions in the eastern provinces.

► The increased final demand in eastern provinces drove SO_2 emissions for all provinces.