Assessment of China's virtual air pollution transport embodied in trade by using a consumption-based emission inventory

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Abstract

High anthropogenic emissions from China have resulted in serious air pollution, and it has attracted considerable academic and public concern. The physical transport of air pollutants in the atmosphere has been extensively investigated, however, understanding the mechanisms how the pollutants were transferred through economic and trade activities remains challenge. For the first time, we quantified and tracked China's air pollutant emission flows embodied in interprovincial trade, using a multiregional input-output (MRIO) model framework. Trade relative emissions for four key air pollutants (primary $PM_{2.5}$, sulfur dioxide (SO_2), nitrogen oxides (NO_x) and non-methane volatile organic compounds (NMVOC)) were assessed for 2007 for each province in China. We found that emissions were significantly redistributed among provinces due to interprovincial trade. Large amount of the emissions were embodied in the imports of east regions from northern and central regions; these were determined by differences in the regional economic status and environmental policies. It is suggested that measures should be introduced to reduce air pollution by integrating cross-regional consumers and producers in national agreements to encourage efficiency improvement in the supply chain and optimizing consumption structure internationally. The consumption-based air pollutant emission inventory developed in this work can be further used to attribute pollution to different economic activities and final demand types with the aid of air quality models.

1 Introduction

China's rapid industrialization since 2000 has been accompanied by large increases in emissions of air pollutants, such as sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO), non-methane volatile organic compounds (NMVOC) and black carbon (BC) (Ohara et al., 2007; Lin et al., 2010; Zhang et al., 2009). In turn, the visible degradation of air quality in China has made environmental and health issues a major focus of policy (Yang et al., 2013; Boldo et al., 2006; Bell et al., 2007). The ambient particulate matter is considered as the most substantial health risks in China, having contributed to 1.2 million premature deaths and removing 25 million healthy years of life in 2010 alone (Yang et al., 2013). The related economic costs are also enormous: the human health impacts of PM_{10} in urban areas of China were estimated to be almost 74 billion dollars in 2010 (Yu et al., 2013) — nearly 1.3% of China's gross domestic product for that year. In response, China's government announced its Action Plan for Air Pollution Control in September 2013 with the purpose of supporting efforts to reduce air pollution. In this plan, air quality and economic development are of equal importance in assessing the performance of government officials at local, provincial and national levels.

Pollution abatement has to begin with an understanding of pollution sources. Previous researches have therefore focused on bottom-up inventories of pollutant emissions over China, based on energy statistics and datasets of technology in use (e.g., Zhang et al., 2007; Zhang et al., 2009; Streets et al., 2003; Lei et al., 2011). These inventories assign emissions to where pollutants are physically produced, which results in production-based pollution accounting. The bottom-up inventories have been extensively used in Chemical transport models to predict and interpret air pollutions, or used to guide the implementation of emission control measures.

As part of efforts to improve air quality, the Chinese government has imposed strict regulations on pollutant emissions in mega-cities. However, if the response is to shift industry out of these cities without changing consumption patterns, the result of the regulations may be an increase in the total amount of pollutant emissions, since there will be an increase in emissions through transportation along the geographically extended supply chains and also because that the general low efficient production in less regulated areas. The redistribution in emissions could have potential significant effects on regional air quality. For example, roughly one-third of the electricity consumed in Beijing is generated in Inner Mongolia (Liu et al., 2012a). Stricter regulations of the power sector in Beijing will tend to increase the import of electricity if similar actions are not taken in Inner Mongolia. Given this connection, the most cost-effective means of reducing emissions from the power sector in Inner Mongolia might not only be deploying new generation technologies there, but also conserving energy in Beijing—as well as facilitating technological cooperation between these two regions (Liu et al., 2013; Lindner et al., 2013). In this regard, effective and cost-effective management of air quality may therefore require policies that cover the entire supply chain, which in turn will depend upon quantitative understanding of the transport of emissions between producers and consumers.

Indeed, this dynamic consequence has already been demonstrated in the case of CO_2 emissions: high levels of consumption in China’s developed coastal regions are driving CO_2 emissions in interior provinces, where CO_2 emission intensity is much greater (Feng et al., 2013). As a result, large quantities of emissions are embodied in the goods traded among provinces, and the less developed regions bear a disproportionate share of the costs for both the pollution and its mitigation. Recent work has demonstrated that the effectiveness of efforts to decrease pollution depend on understanding not only where pollutants are produced, but also where the goods and services related to the pollution are ultimately consumed (Davis and Caldeira, 2010; Davis et al., 2011; Feng et al., 2013; López et al., 2013; Guan et al., 2014a). Lin et al. (2014) demonstrated that China’s international trade has significant impact on global air quality by linking the Input-Output model with emission inventory and air quality model. However, the transport of air pollutant emissions through economic and trade activities among different regions in China are not well established yet.

In this study, we developed a consumption-based air pollutant emission inventory framework at provincial scale to explore the emission flows embodied in supply chains in China. With this framework, we estimated emissions of four air pollutants (primary $PM_{2.5}$ and its key precursors SO_2, NO_x and NMVOC) embodied in goods and services traded among 30 provinces or municipalities in China for 2007. We used a multiregional input-output (MRIO) model to reallocate emissions from the provinces where they were produced to the provinces where the related products were ultimately consumed. Given China's substantial international trade, a sizable proportion of pollution is related to goods that are ultimately consumed in other countries. We allocated such emissions to a single "out-of-China" region. To better assess consumption patterns, we also assessed the contribution of four different categories of consumption: urban household, rural household, government and capital formation. The consumption-based air pollutant emission inventory developed in this work can then be used to attribute pollution to different economic sectors and final demand types with the aid of air quality models. It should be noted that our consumption-based accounting procedure should not be interpreted as assigning all economic or ethical responsibility for pollution to consumers (Wiedmann, 2009; Davis and Caldeira, 2010; Guan et al., 2014a); it represents a critical source of information for consideration by decision makers, who design public policy accordingly.

This paper is organized as follows: In Section 2, we describe key principles of consumption-based accounting and details of our MRIO model, including the sources and treatment of raw economic data. Section 3 presents consumption-based emissions at provincial level and pollutant emissions embodied in traded products. Sections 4 discuss the possible impacts of current policies according to our finding and related policy implication.

2 Methodology and data

2.1 MRIO analysis

Since developed by Leontief (1970), environmental extended input-output analysis has been widely used to analyze the drivers and causes of global and regional environmental changes in many different contexts (Wiedmann et al., 2007; Hertwich and Peters, 2009; Minx et al., 2009; Suh, 2009; Guan and Barker 2012). In the past several years, environmental extended MRIO models have been developed to quantify global CO_2 emissions embodied in international trade, initially for a specific year (Davis and Caldeira, 2010 ; Feng et al., 2012), and later over multiple years (Peters et al., 2011). More recently, sectoral resolution of an input-output table has been improved to allow MRIO analysis among 187 countries and 15909 sectors (Lenzen et al., 2012, 2013). Liu et al. (2012) developed a MRIO model that consist of 30 sectors and 30 provinces in China, and have been widely used to assessing CO_2 emissions embodied in trade flows among China and internationally in 2007 (Feng et al., 2013). Here, we apply this Chinese MRIO in 2007 to quantify non-CO_2 air pollutants embodied in goods and service traded among China's provinces and internationally. We summarize the model and data sources bellow.

The Chinese MRIO framework begins with the accounting balance of monetary flows:

$$\mathbf{x}^r = \mathbf{A}^{rr}\mathbf{x}^r + \mathbf{y}^{rr} + \sum_{s \neq r} \mathbf{A}^{rs}\mathbf{x}^s + \sum_{s \neq r} \mathbf{y}^{rs} + \mathbf{y}^{re} \tag{1}$$

Here, r and s indicate province r (producer) and s (consumer); $\mathbf{x}^r$ and $\mathbf{x}^s$ are, respectively, the vectors for sectoral total outputs in province r and s; $\mathbf{A}^{rr}\mathbf{x}^r$ represents the industry requirements to produce its regional final products and $\mathbf{A}^{rr}$ is a matrix with its columns representing specific sectors' local inputs required to produce one unit output; $\mathbf{A}^{rs}\mathbf{x}^s$ and $\mathbf{A}^{rs}$ represents the cross-regional industry requirement import from province r to province s and its coefficients to produce one unit output; $\mathbf{y}^{rr}$ is a vector with its elements representing final consumption (urban and rural household, government and capital formation) produced in province r; $\mathbf{y}^{rs}$ is the cross-regional final products supply from province r to s; and $\mathbf{y}^{re}$ is a vector indicating region r's sectoral products for international export. Evaluating the equation for all sectors and all provinces, we construct a matrix that represents the entire Chinese domestic economy, including its export:

$$\begin{pmatrix} \mathbf{x}^1 \\ \mathbf{x}^2 \\ \vdots \\ \mathbf{x}^m \end{pmatrix} = \begin{pmatrix} \mathbf{A}^{11} & \mathbf{A}^{12} & \cdots & \mathbf{A}^{1m} \\ \mathbf{A}^{21} & \mathbf{A}^{22} & \cdots & \mathbf{A}^{2m} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{A}^{m1} & \mathbf{A}^{m2} & \cdots & \mathbf{A}^{mm} \end{pmatrix} \begin{pmatrix} \mathbf{x}^1 \\ \mathbf{x}^2 \\ \vdots \\ \mathbf{x}^m \end{pmatrix} + \begin{pmatrix} \sum_r \mathbf{y}^{1r} + \mathbf{y}^{1e} \\ \sum_r \mathbf{y}^{2r} + \mathbf{y}^{2e} \\ \vdots \\ \sum_r \mathbf{y}^{mr} + \mathbf{y}^{me} \end{pmatrix} \tag{2}$$

Here m indicate the total region's number, and m=30 in this research.

When solved from the total output, Eq. (2) can yield the following:

$$\mathbf{x} = (\mathbf{I}\text{-}\mathbf{A})^{-1}\mathbf{y} \tag{3}$$

The bolded uppercase and lowercase letters in equation 3 represent the corresponding matrixes and vectors in Eq. (2), respectively. $(\mathbf{I}\text{-}\mathbf{A})^{-1}$ is the Leontief inverse matrix.

Pollutant emissions (here refers to primary $PM_{2.5}$, SO_2, NO_x and NMVOC, see section 2.4 below) are then calculated by incorporating a vector of emission intensity:

$$\mathbf{e} = \hat{\mathbf{f}}(\mathbf{I}-\mathbf{A})\mathbf{y} \tag{4}$$

where $\hat{\mathbf{f}}$ means a diagonal matrix with the elements of vector **f** on its main diagonal and all other entries equal to zero; component f_i^r in **f** is the direct emission intensity vector calculated by sector *i*'s total emissions divided by its total output in a given region *r* (Hubacek and Sun, 2005; Lin et al., 2014; Guan et al., 2014b).

2.2 Emissions embodied in interprovincial and international trade flows

Using the pollutant emissions calculated by the Chinese MRIO, we quantify the emissions embodied in trade flows among China's provinces and in trade between those provinces and other countries. By disaggregating the final demand of each province in Eq.(4), we could quantify emissions of each pollutant embodied in the goods and services consumed in each province as well as where the emissions were produced. For example, the final demand of province *r* is $\mathbf{y}_c^r = (\mathbf{y}^{1r} \quad \mathbf{y}^{2r} \quad \cdots \quad \mathbf{y}^{rr} \quad \cdots \quad \mathbf{y}^{mr})'$, and it includes products produced in province *r* ($\mathbf{y}^{rr}$) as well as final products imported from other regions ($\sum_{s\neq r}\mathbf{y}^{sr}$). Using this vector as **Y** in Eq. (4) gives the emissions embodied in the final consumption of province *r*:

$$e_c^r = \sum_{s=1} e_c^{sr} = \sum_{s=1} \mathbf{f}^s(\mathbf{I}-\mathbf{A})^{-1}\mathbf{y}_c^r \tag{5}$$

where $\mathbf{f}^s$ is a vector of the corresponding sectoral pollution intensities for region *s* but zeros for all others'; e_c^r represents total pollutant emissions embodied in region *r*'s consumption that were produced within China; it excludes emissions embodied in any interprovincial exports, and includes imports (e_c^{sr}, $r\neq s$). The solution is region and sector specific.

Pollutants embodied in international exports can be calculated by isolating the demand **Y** for exports, $\mathbf{y}^e$:

$$e^e = \sum_{r=1} e^{re} = \sum_{r=1} \mathbf{f}^r (\mathbf{I} - \mathbf{A})^{-1} \mathbf{y}^e \tag{6}$$

here e^{re} indicates province r's emission embodied in international exports.

We also attempt to estimate the emissions embodied in international imports. We begin with a simplifying assumption that imported products were produced under the same industrial structure and technology in China (Tang et al., 2012). This gives emissions avoided by import (EAI):

$$e_{EAI} = \sum_{r=1} e_{EAI}^r = \mathbf{f}(\mathbf{I} - \mathbf{A})^{-1} \mathbf{y}^{\mathrm{Im}} \tag{7}$$

To obtain the pollution embodied in each province's imports, we assume that China's total import form nation i was proportionally distributed to each province; then we adjusted the e_{EAI} of each province by a coefficient, u_r, which reflects the producing nations' average pollution intensity (Lin et al., 2014):

$$\mu_r = \sum_i \frac{NI_i}{PI_r} \times \frac{N_i^{\exp}}{C^{tim}} \tag{8}$$

NI_i indicates nation i's pollutant intensity; PI_r signifies province r's pollutant intensity; $N_i^{\exp}$ indicates nation i's total export to China; C^{tim} signifies China's total import. Thus, the emission embodied in international imports to province r is $\mu_r e_{EAI}^r$.

As in the study by Liu et al. (2012b), the data required for Chinese MRIO were derived from provincial input-output tables (National Bureau of Statistics, 2011). The trade data between China and the other countries used in this section for China's international trade were aggregated from the China Foreign Economic Statistical Yearbook (National Bureau of Statistics, 2008a) and the China Trade and Economic Statistical Yearbook (National Bureau of Statistics, 2008b). Provincial input-output tables (National Bureau of Statistics, 2011) were used to supplement and modify the international import data.

2.3 Consumption-based emissions by province

Consumption-based emissions represent the quantities of pollution related to all the goods and services consumed by a given province (Peters, 2008; Peters and Hertwich, 2008; Davis and Caldeira, 2010; Lin et al., 2014; Lindner and Guan 2014). The gross flows of emissions embodied in trade can thus be used to quantify consumption-based emissions—by adding emissions embodied in imports to and subtracting emissions embodied in exports from the emissions physically produced in each province:

$$CE = PE - INE - IPE + INI + IPI \tag{9}$$

CE and PE indicate regional pollution inventories under the consumption and production perspectives, respectively; INE and INI signify the emissions embodied in international exports and imports, respectively; IPE and IPI indicate emissions embodied in interprovincial exports and imports.

2.4 Production-based inventory data

The vector of pollution intensity, **f**, in equation 4 and 7 is derived from the multi-resolution emission inventory for China (MEIC: http://www.meicmodel.org) compiled by Tsinghua University. The MEIC is a production-based inventory, updated from the widely used INTEX-B dataset (Zhang et al., 2009). The inventory covers 31 provinces or autonomous regions, 10 pollutants (e.g., SO_2, NO_x, CO, NMVOC, BC, $PM_{2.5}$, PM_{10}, Ammonia (NH_3), organic carbon (OC), and CO_2) and ~700 emitting sources categories. In this study, we used the energy balance table of each province from the China Energy Statistical Yearbook (National Bureau of Statistics, 2008c) and the revised sectoral energy consumption from China Economic Census Yearbook (National Bureau of Statistics, 2010) to map the MEIC emission data onto the sectors in our Chinese MRIO (Guan et al., 2014c). The sector classification appears in Appendix A1 (the total 30 sectors had been aggregated into 27 sectors allowing for the consistency between MRIO and emission sectors). Global emissions were taken from EDGAR v.4.2 (http://edgar.jrc.ec.europa.eu/) to calculate aggregated pollution intensities of other countries (see equation 8).

3 Results

3.1 Production-based emissions by consumption types

Production-based air pollutant emissions can be divided into three categories according to their service destinations: local consumption, other regions' consumption within China through interprovincial export, and other countries' consumption through international export. On average, we found that emissions from local consumptions contributed 62%, 46%, 46%, and 56% of national total emissions for primary $PM_{2.5}$, SO_2, NO_x, and NMVOC respectively, with large variations among different provinces. Higher contributions for primary $PM_{2.5}$ and NMVOC could be attributed to emissions from direct energy consumption in residential sector. Regionally, contributions from each category vary by provinces as their different trade patterns and regional attributes. Fig. 1 uses SO_2 as example to demonstrate production-based emissions of 30 provinces in China and the contribution of each category. Highest contribution from local consumption occurred in Sichuan (69%) and Jiangxi (68%), indicating high self-sufficiency in these regions. While lowest contribution from local consumption occurred in east coast regions such as Tianjin (24%) and Shanghai (27%).

3.2 Consumption-based emissions by province

Table 1 compares the production-based and consumption-based pollutant emissions in 2007 for all 30 provinces in mainland China. For the provinces where service industries and light industries are highly developed, consumption-based emissions were greater than production-based emissions since they are highly dependent on products or energy imported from other provinces. For example, Beijing's consumption-based emissions are 2.6-, 3-, 1.6- and 1.5-fold its consumption-based emissions for primary $PM_{2.5}$, SO_2, NO_x and NMVOC, respectively; about 74-83% of its consumption-based emission were imported. In provinces whose economy is dependent on energy generation, heavy industry, or materials manufacturing, production-based emissions were much greater than consumption-based emissions. For example, in Hebei, 63% of primary $PM_{2.5}$, 67% of SO_2, 68% of NO_x and 56% of NMVOC emissions were related to products consumed outside Hebei. Similarly, consumption-based emissions in Shanxi and Inner Mongolia were 26-62% lower than production-based emissions. This difference indicates that over 50% of their total pollutants emissions were embodied in producing interprovincially or internationally exported products. For Anhui, Sichuan and Guangxi, they had similar emissions for these two accounting methods, as substantial proportions of the goods produced in these provinces were consumed locally. In these provinces, emissions were largely related to residential direct energy consumption (accounted for here as the emission service for regional consumption).

According to the input-output analysis, regional final consumptions can be divided into four categories: urban households consumption, rural households consumption, government consumption and capital formation. For the emissions caused by domestic rural and urban residential direct consumption, they were listed as independent final categories as they are irrelevant to economic production system, and named as rural_direct and urban_direct in this research.

Figure 2 presents pollutant emissions caused by each final consumption category among the 30 provinces. Capital formation and urban residential consumption dominated the consumption-based emission of SO_2 and NO_x in all the provinces, reflecting large-scale nationwide expansion of infrastructure. Among the 30 regions, the capital formation of Shandong contributed most to national consumption-based SO_2 (5% of national total) and NO_x (3% of total) emissions; this was followed by Jiangsu, Zhejiang, and Guangdong. For primary $PM_{2.5}$ and NMVOC, capital formation and direct rural residential energy consumption dominated the total consumption-based emissions in almost all provinces. In Beijing, Jiangsu, Shanghai, Zhejiang and Guangdong, biomass combustion is not used as a significant energy source; thus, capital formation and urban residential consumption activities dominated those regions' total consumption-based emissions. For less developed regions, such as Guangxi, Guizhou, Anhui and Sichuan, biofuel is still be an important energy source, so the related combustion emission accounts for over 50% of regional consumption-based emissions for primary $PM_{2.5}$ and NMVOC.

3.3 Emissions embodied in interprovincial trade flows

Figure 3 shows the balance of air pollutants embodied in products traded among the 30 provinces in 2007. Nationally, 3.1 Tg of primary $PM_{2.5}$ (23% of total Chinese production-based emission), 10.5 Tg of SO_2 (33% of total), 7.6 Tg of NO_x (31% of total) and 4.7 Tg of NMVOC (23% of total) were emitted during the production of products or service that were ultimately consumed in other provinces or regions in China. Economically advanced regions, such as Beijing, Tianjin, Shanghai, Jiangsu, Zhejiang and Guangdong were net importers of emissions, whereas, areas of heavy industry or manufacturing bases, such as Hebei, Shanxi, Henan, Inner Mongolia and Shannxi were net exporters of emissions.

Pollutants embodied in intermediate products make up a large portion of the pollutants embodied in interprovincial trade. This indicates that most of the goods being traded had supply chains that covered multiple provinces, with relatively few products being entirely manufactured in one province for consumption in local region. This indicates a strengthened interregional cooperation in manufacturing pattern. For emissions embodied in interprovincial exports, the ratio between finished goods and intermediate goods varies from 1:1 to 1:12 across the provinces. The lowest ratio is 1:12 for Shanxi, which exported large amounts of energy to Beijing, Tianjin and some other regions in southern China. The finished-to-intermediate ratio of emissions embodied in imports was similarly variable, ranging from 1:1 to 1:13. The lowest ratio amounted to 1:13 for Zhejiang, which imported large volumes of intermediate products from the Central, North and Northwest regions to support its local industries.

Figure 4 presents the largest net flows of embodied pollutants among the eight regions (listed in Table A2 in Appendix A). From the perspective of technology development, there was an increasing trend in pollutant intensity from southeast to northwest China for all the four pollutants. The Northeast had the highest emission intensities for SO_2 (223 Mg/100 million CNy^{-1}), NO_x (145 Mg/100 million CNy^{-1}) and NMVOC (74 Mg/100 million CNy^{-1}); and Central had the highest emission intensity for primary $PM_{2.5}$ (50 Mg/100 million CNy^{-1}). In contrast, the lowest emission intensity occurred in the South Coast (39 Mg/100 million CNy^{-1} for SO_2 (49 Mg/100 million CNy^{-1} for NO_x) and Beijing-Tianjin (13 Mg/100 million

CNy^{-1} for $PM_{2.5}$ and 41 Mg/100 million CNy^{-1} for NMVOC). In terms of pollution transfer, affluent areas, such as the Beijing-Tianjin, East Coast and South Coast regions, were net pollution importers owing to their relatively advanced economic development and modernized production technologies (and thus lower pollution intensity). For example, primary $PM_{2.5}$ emissions embodied in imports to the East Coast region are four times higher much than those embodied in exports; the figures for SO_2, NO_x and NMVOC are 3-, 2- and 1.5-fold, respectively. About 80% of the emissions embodied in East Coast's imports occur in the North, Central and Northeast regions. In Beijing-Tianjin, the pollutants embodied in imports exceeded those embodied in exports by factors of 4.5, 4, 3 and 2 for primary $PM_{2.5}$, SO_2, NO_x and NMVOC, respectively. Further, 46% of the primary $PM_{2.5}$, 27% of SO_2, 28% of NO_x and 24% of NMVOC embodied in Beijing-Tianjin's imports derived from the North region (including Hebei and Shandong). In contrast, less economically developed areas in the North, Central, Northwest and Southwest regions were net exporters, with large quantities of emissions outsourced by East and South Coast regions.

3.4 Emissions embodied in international trade flows

Figure 5 presents the emissions embodied in internationally traded products at the provincial level. In keeping with China's role as the world's largest exporter, most provinces have a trade deficit in embodied emissions. Shandong was the largest exporter with 260 Gg of primary $PM_{2.5}$, 833 Gg of SO_2, 687 Gg of NO_x and 470 Gg of NMVOC embodied in international exports, accounting for 11-13% of the total emissions embodied in China's international exports, followed by Guangdong, Hebei, Zhejiang and Jiangsu. Simultaneously, the coastal regions also had high imported emissions. Guangdong had the largest pollutant imports (77 Gg primary $PM_{2.5}$, 345 Gg SO_2, 230 Gg NO_x and 531 Gg NMVOC), those accouned for 16, 18, 16 and 21% of China's total imports of primary $PM_{2.5}$, SO_2, NO_x and NMVOC, respectively, followed by Shanghai, Jiangsu, Zhejiang and Beijing.

A province may make a final product for international export, but it can also make an intermediate product for another province's international export. The former process leads to emissions embodied in direct international export, whereas the latter leads to emissions associated with other regions' international export. The international exports from the coastal areas (Guandong, Fujian, Shanghai, Zhejiang, Jiangsu, Tianjin and Shandong) account for 82% of all Chinese exports. However, the associated embodied emissions were only 43, 41, 52 and 60 % of China's total export-embodied emissions for primary $PM_{2.5}$, SO_2, NO_x, and NMVOC, respectively. Figure 6 presents the largest cross-regional flows of emissions embodied in intermediate products caused by international exports production, which can explain the differences. We found that, in coastal regions, approximately 50% of emissions embodied in international trade were transferred to Central, Northwest and Southwest regions through intermediate products.

We estimated that 2.0 Tg of primary $PM_{2.5}$ (15% of total Chinese production-based emission), 7.0 Tg of SO_2 (21%), 5.7 Tg of NO_x (23%) and 4.3 Tg of NMVOC (21%) are embodied in goods or services exported internationally, which are lower than the estimates in Lin et al. (2014). The differences between Lin et al. (2014) and this work are mainly due to differences in methodologies. Lin et al. (2014) used a Single-Region Input-Output (SRIO) model, while we used a Multi-Region Input-Output (MRIO) model framework. SRIO used national average emission intensity when calculating export embodied emissions, which will overestimate emissions in coastal provinces where emission intensities are lower than national average. In MRIO framework, embodied emissions were calculated for each province using its own emission intensity. Estimates in Lin et al. (2014) would be then higher than ours, as export embodied emissions are dominant by coastal provinces.

4 Policy Implications

4.1 Impact from infrastructure construction

Emissions related to construction-dominated capital formation accounted for 50% of all China's consumption-based emissions of air pollutants, corresponding to the increased urbanization rate from 26% in 1990 to 53% in 2013 in China (National Bureau of Statistics, 2014). The rapid urbanization has created a boom in the demand for materials and infrastructure; it has greatly accelerated industrial production and infrastructure construction—and therefore also the related pollutant emissions (Heinonen and Junnila, 2011). Recently, the implementation of the "New Socialist Countryside" which is aimed to improve living condition in countryside by unify planning and constructing, would result in a wave on construction in rural areas nationwide. This rapid construction will drive the exploration and production of natural resources as well as related pollution emissions. In addition, the average life span of building in China is 35 years—much less than the 74 years of the United States and 132 years of the United Kingdom (China Economic Review, 2013). Rapid increasing in construction will aggravate this phenomenon.

Recent studies have shown that China's current technology improvements will be barely able to offset the pollution emissions associated with increasing consumption (Liang et al., 2014; Guan et al., 2014b). However, China's government has to continue to promote the economic growth to improve livelihoods and defeat environmental problem. Thus, to achieve pollution reduction targets, the government needs to focus on key source sectors and technologies; however, it also need to pay greater attention to control and management strategies with respect to consumption. Our study indicates that, the key regulatory policies should focus on construction sector, such as promoting the use of energy-saving building materials, increasing the life span of building, thus decrease the related upstream emissions along the supply chains. Simultaneously, advocating saving behaviors in daily life is also essential.

4.2 Importance of interprovincial and international transfer in pollutants

Interprovincial trade in China is accompanied by substantial pollutant transfer. As shown in Fig. 3, 23, 33, 31 and 23% (3.1 Tg ,10.5 Tg, 7.6 Tg and 4.7 Tg), respectively, of China's primary $PM_{2.5}$, SO_2, NO_x and NMVOC are related to goods or services that are ultimately consumed outside of the provinces where they were produced. Most of this pollutants transfer occurs between developing central and western regions and the affluent east coastal regions.

Recently, China's central government has launched nationwide acts to reduce the CO_2 emission (Liu et al., 2012b) and atmospheric pollutants (The State Council of the PRC, 2013), with stricter measures being implemented for eastern than western provinces. This disparity in mitigation targets is likely to accelerate the relocation of heavy industries to central and west regions, thereby worsening the atmospheric environment in those less developed regions. As evident in Fig. 4, the production-related pollutant intensities of the eight regions showed a gradually increasing trend from the developed southeast to less developed northwest regions. This means that more pollutants were emitted to make one product unit in central and west regions. Relocating industries will thus redistribute the environmental problem rather than eliminate it—aka the 'beggar-thy-neighbor' effect. Increasing interprovincial trade will also drive traffic flows, which have been a key contributor to atmosphere pollutants emissions (Cheng et al., 2013). Thus this kind of industrial shift may ultimately increase total national pollutant emissions to some extent.

Since air pollutants can be transported over a great distance in the atmosphere (Lin et al., 2014), outsourced emissions in developing provinces may blow back to the developed provinces under favorite metrological conditions (Ying et al., 2014). Hence, an effective regional pollution control strategy would target a reduction in total emissions rather than simply relocating emissions. Technology transfer between developed and developing regions should play a leading role in joint actions for regional or interregional air pollution control. For developed regions, industrial transfer should be accompanied by technology transfer; for less developing regions, higher emission standard should be established for new installations that exceed a fixed benchmarking, thus reducing the increment of emissions.

Economic mechanisms could also provide alternative ways by involving both producers and consumers in emissions mitigation. The pilot phase of China’s Emissions Trading Scheme (ETS) on CO_2, SO_2, and NO_x has proven its effectiveness in emission reductions, expanding the ETS system across China can be used to mitigate air pollutant emissions. Taxes can be used to transfer environmental impacts to consumers, thus reduce the consumption volume and related emissions. Economic stimulus or penalty instigated by leading companies can help reduce the emissions of its suppliers more effectively as companies are the agents that decide to outsource their production chains (O’Rourke, 2014), thus can exerting a cleaning effect on its upstream supply chains more easily (Skelton, 2013). Eco-Labelling system could achieve efficiency gains by producers which can be monitored by regulative bodies. Consumer choices in eco-labelling can be a great incentive for companies to adopt such scheme in order to promote market competitiveness (Grundey and Zaharia, 2008). Although China has achieved great progress in technology improvements and pollution intensity reduction, total emissions are still on the rise as improvements in technology efficiency were offset by increasing consumptions (Liang et al., 2014; Guan et al., 2014). Taxes can be used to transfer environmental impacts to consumers, thus reduce the consumption volume and related emissions.

The results also indicated that substantial leakage of emissions from foreign countries to China via international trade. The pollution embodied in international trade accounted for 15-23% of total pollutants emission produced in China. Furthermore, 41-60% of the embodied emissions occurred in Tianjin, Shandong, Jiangsu, Shanghai, Zhejiang, Fujian and Guangdong, all of which are located in the China's three biggest industrial bases (Jing-Jin-Ji, Yangtze River delta and Pearl River delta) and where air pollutions is severe. Thus, reduction policies related to export adjustment should tend to focus on these key export-oriented regions, as well as the exported products that involve multi-sector and multi-regional supply chains but with low add valve (Skelton et al., 2011 Skelton, 2013). An economic stimulus or penalty instigated by an export-oriented company can help reduce the emissions of its suppliers, thereby exerting a cleaning effect on its upstream supply chains (Skelton, 2013).

5 Concluding Remarks

In this work, we used a MRIO framework to estimate consumption-based air pollutant emissions for China for the year 2007 at provincial level. This is the first time that the virtual air pollutant emission transport embodied in interprovincial trade was quantified and tracked. We found that coastal provinces outsourced large quantities of emissions to inland provinces through import of goods. Emissions have been significantly redistributed due to interprovincial trade. Future work can link our provincial level consumption-based inventory and the pollution flows with chemical transport models, to investigate the impacts of trade activities on regional and global air quality.

Our MRIO analysis traced pollutant sources related to consumption activities. It clearly illustrates the extent and structure of externalization of pollutants, and it presents a reasonable approach to facilitating collaboration between producers and consumers. This approach appears to present an effective way to optimize air quality management decisions toward environmentally sustainable economic growth. Although the results derived from this work could help the policy makers to better understand the responsibility of pollution from consumption perspective, it should be noted that splitting the share of responsibility between producers and consumers is more complicated as producers also gain economic benefit when emitting pollutants (Barrett et al., 2013). Application of shared responsibility criterion (e.g., Gallego and Lenzen, 2005; Lenzen,et al., 2007; Cadarso et al., 2012; Hoekstra and Wiedmann, 2014) which involves both producers and consumers in emission reduction could help developing provinces in China to assume the increase of costs derived from mitigation policies and contribute to a better solution of the problem.

Acknowledgements

This study was supported by China's National Basic Research Program (2014CB441301) and the National Science Foundation of China (41222036, 71322304, 41328008, 41175127, 41422502 and 71341025). Q. Zhang and K. B. He are supported by the Collaborative Innovation Center for Regional Environmental Quality.

Appendix A

Table A1 Sectors classification for MRIO Table

Sector number	Sector Name
1	Agriculture
2	Coal mining and processing
3	Crude petroleum and natural gas products
4	Metal ore mining
5	Non-ferrous mineral mining
6	Manufacture of food products and tobacco processing
7	Textile goods
8	Wearing apparel, leather, furs, down and related products
9	Sawmills and furniture
10	Paper and products, printing and record medium reproduction
11	Petroleum processing and coking
12	Chemicals
13	Nonmetal mineral products
14	Metals smelting and pressing
15	Metal products
16	Machinery and equipment
17	Transport equipment
18	Electric equipment and machinery
19	Electronic and telecommunication equipment
20	Instruments, meters, cultural and office machinery
21	Handicrafts and other Manufacturing
22	Electricity, steam and hot water production and supply
23	Gas and water production and supply
24	Construction
25	Transport and warehousing, Post and telecommunication
26	Wholesale and retail and catering accommodation
27	Others

Table A2. Region divisions

Region	**Provinces/municipalities that included in each region**
Beijing-Tianjin	Beijing and Tianjin
North	Hebei and Shandong
Northeast	Liaoning, Jilin and Heilongjiang
East Coast	Jiangsu, Shanghai and Zhejiang
Central	Shanxi, Henan, Anhui, Hunan, Hubei and Jiangxi
South Coast	Fujian, Guangdong and Hainan
Southwest	Sichuan, Chongqing, Guizhou, Yunnan, Guangxi (and Tibet)
Northwest	Shannxi, Gansu, Qinghai, Ningxia ,Xinjiang and Inner Mongolia

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Table1. Comparison of regional pollutant emissions from production and consumption-based emissions (Gg/year)

Pollutant	**Primary $PM_{2.5}$**		**SO_2**		**NO_x**		**NMVOC**	
Region	Pro	Con	Pro	Con	Pro	Con	Pro	Con
Beijing	111	285	261	775	385	629	372	571
Tianjin	127	183	429	548	361	445	286	326
Hebei	974	513	2347	1387	1780	1036	1199	842
Shandong	1276	933	3105	2375	2582	1940	1948	1554
Liaoning	587	416	1189	826	1250	850	900	668
Jilin	316	338	513	735	650	723	512	493
Heilongjiang	370	363	367	475	786	640	705	589
Shanghai	142	338	726	1112	591	838	557	836
Jiangsu	680	689	1544	1375	1777	1356	1571	1339
Zhejiang	368	548	957	1371	1231	1291	1113	1008
Shanxi	755	435	2483	1241	1148	593	653	486
Henan	1015	667	1532	1157	1685	1108	1176	1032
Anhui	555	515	718	667	871	674	812	759
Hubei	542	481	1674	1248	862	695	768	751
Hunan	544	441	1353	1045	730	646	595	556
Jiangxi	286	286	701	906	455	589	348	378
Fujian	261	221	586	516	525	453	430	422
Guangdong	629	669	963	1642	1494	1361	1541	1487
Hainan	34	37	91	82	84	75	100	78
Guangxi	484	439	970	674	467	406	706	643
Chongqing	249	270	1307	1037	367	388	317	353
Sichuan	771	764	1560	1415	747	747	1112	1093
Guizhou	424	318	1841	812	545	302	346	313
Yunnan	383	322	837	628	551	410	462	461
Shaanxi	352	281	1680	858	555	450	521	423
Gansu	218	197	414	352	370	274	329	287
Qinghai	58	48	77	101	92	103	68	70
Ningxia	83	74	519	303	242	167	95	104
Xinjiang	214	206	473	447	479	405	445	307
Inner Mongolia	436	282	1386	570	1182	448	541	384

Pro = production-based emissions; Con = consumption-based emissions

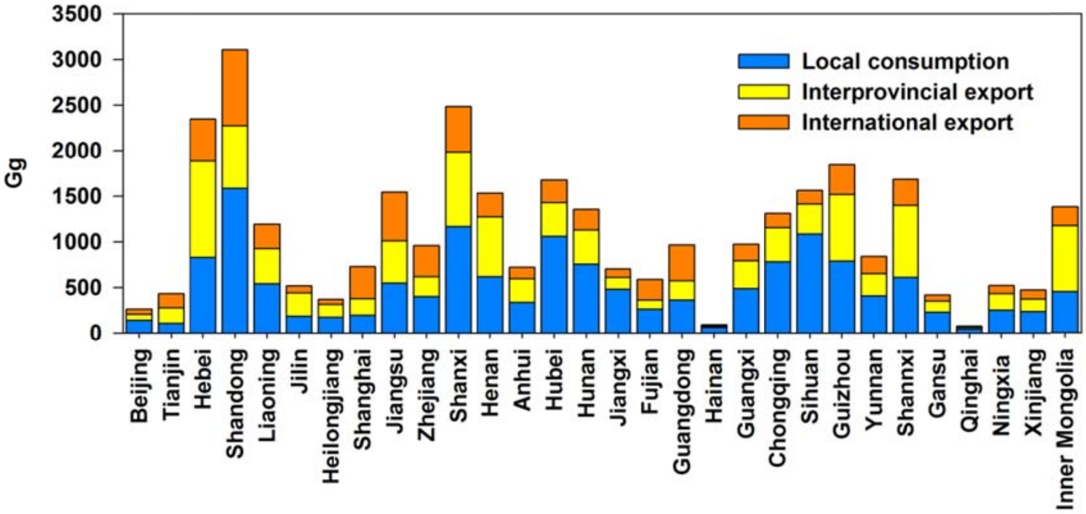

Fig. 1. Production-based SO_2 emissions in 2007 by provinces and consumption locations

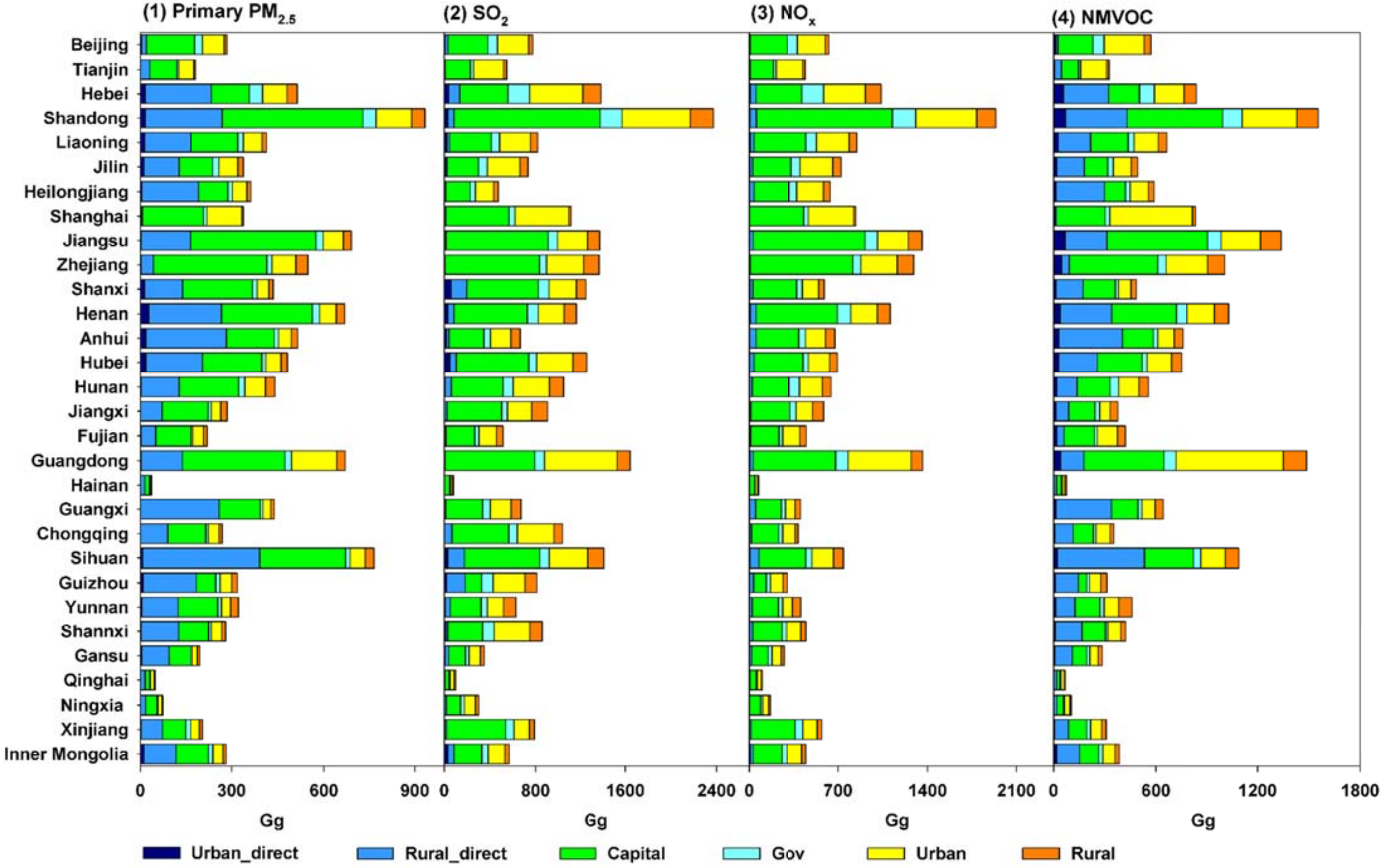

Fig. 2. Consumption-based emissions in 2007 by provinces and final demand categories

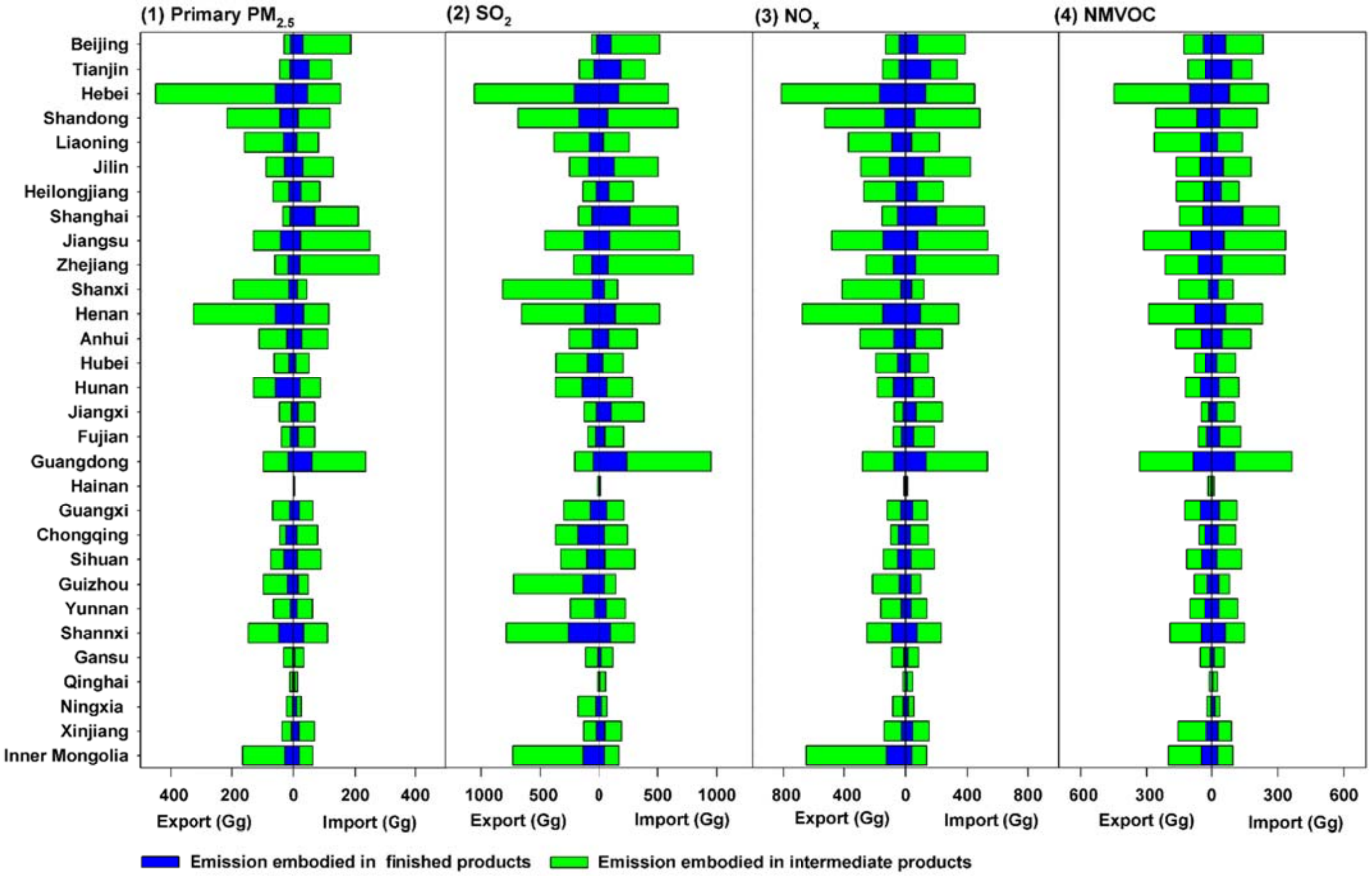

Fig. 3. Balance of air pollutant emissions embodied in each province's interprovincial trade

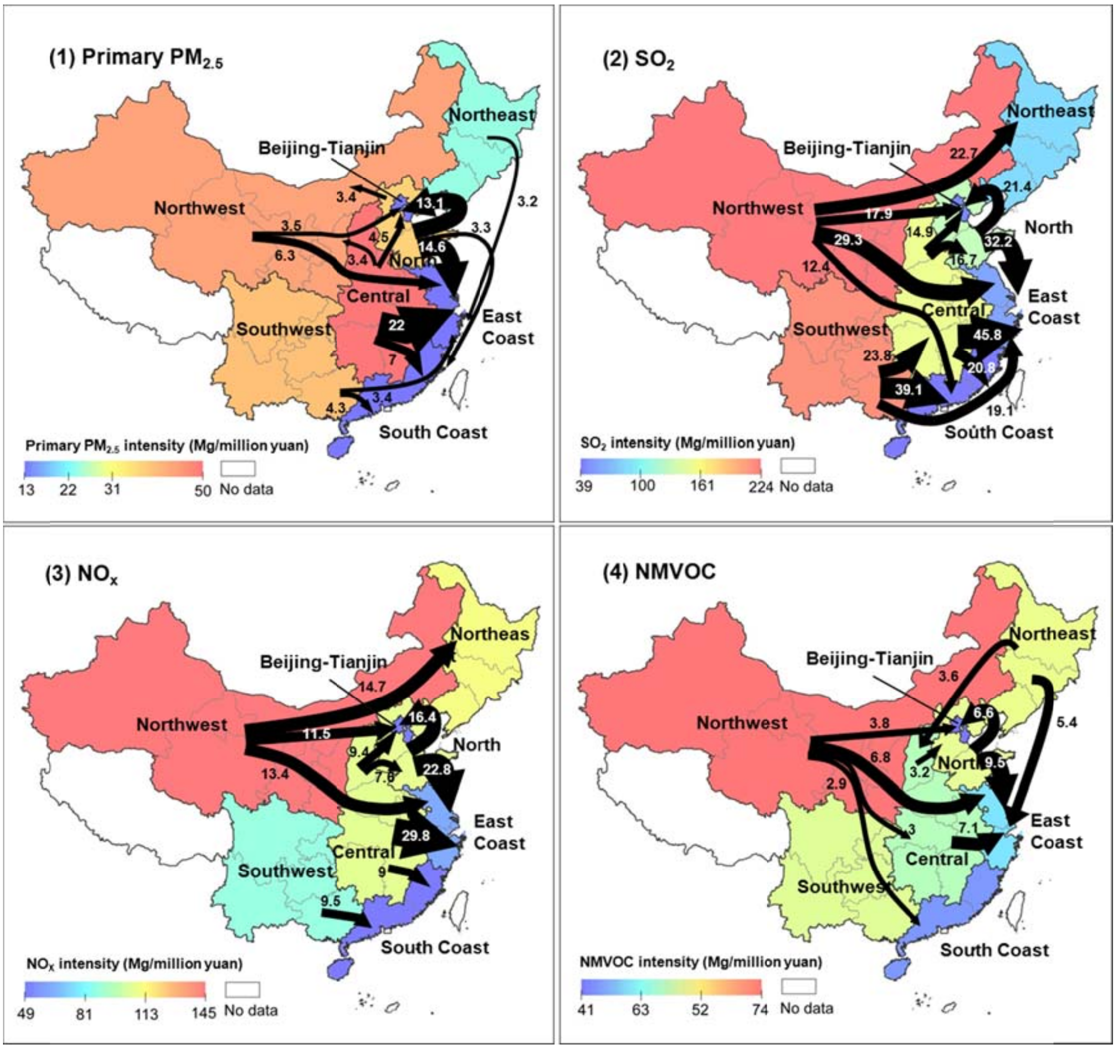

Fig. 4. Largest net flows of primary $PM_{2.5}$, SO_2, NO_x, and NMVOC emissions embodied in interprovincial trade in 2007 (unit of flow: Gg). The shading in each region indicates the related production emission intensity.

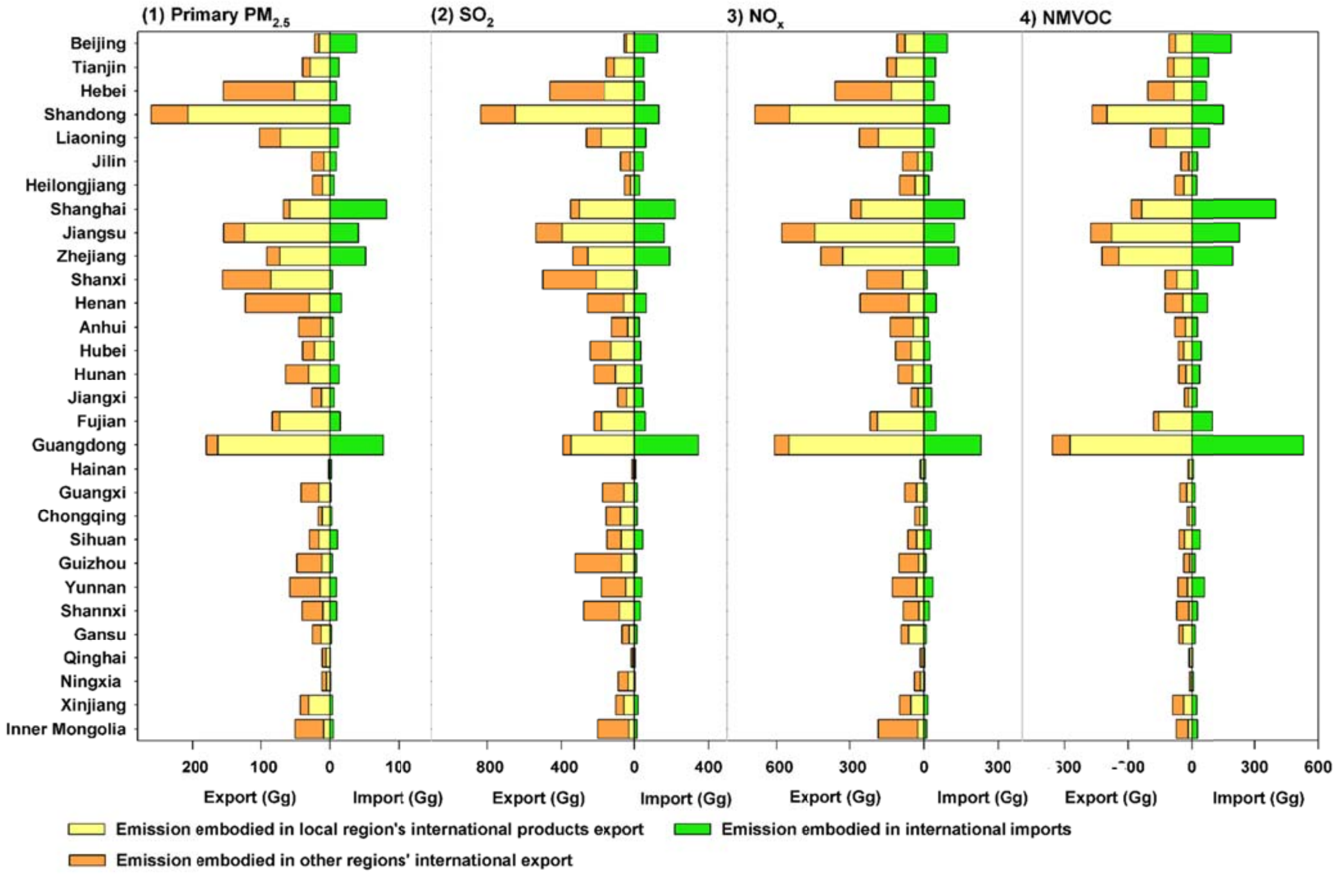

Fig. 5. Balance of pollutant emissions embodied in each province's international trade

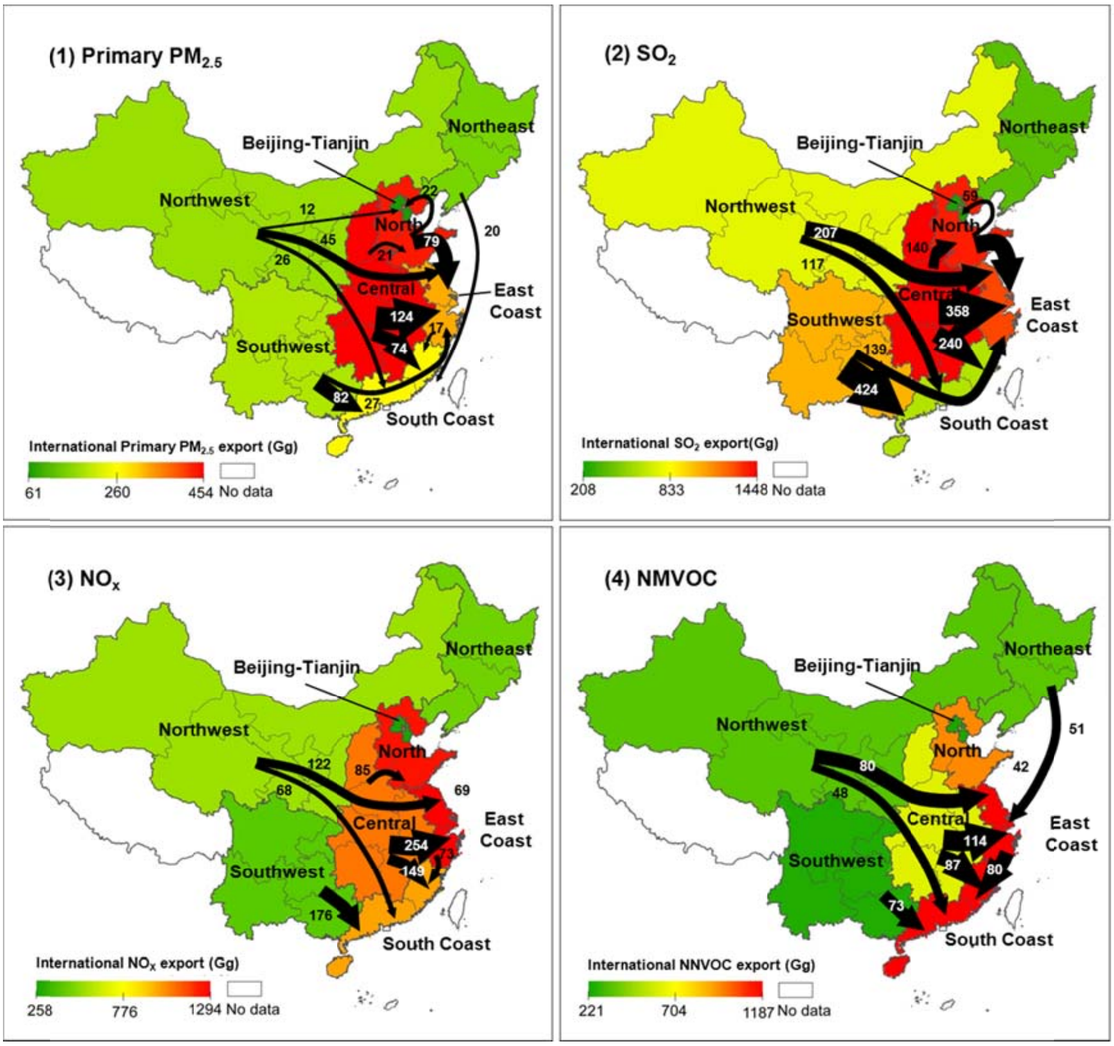

Fig. 6. Regional pollutant emissions due to production of intermediate products to support other regions' international exports (unit of flow: Gg). The shading from green to red indicates each region's total international pollutant exports.