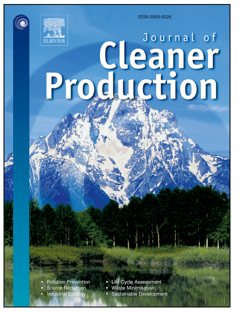

Inter-regional spillover of China's sulfur dioxide (SO_2) pollution across the supply chains

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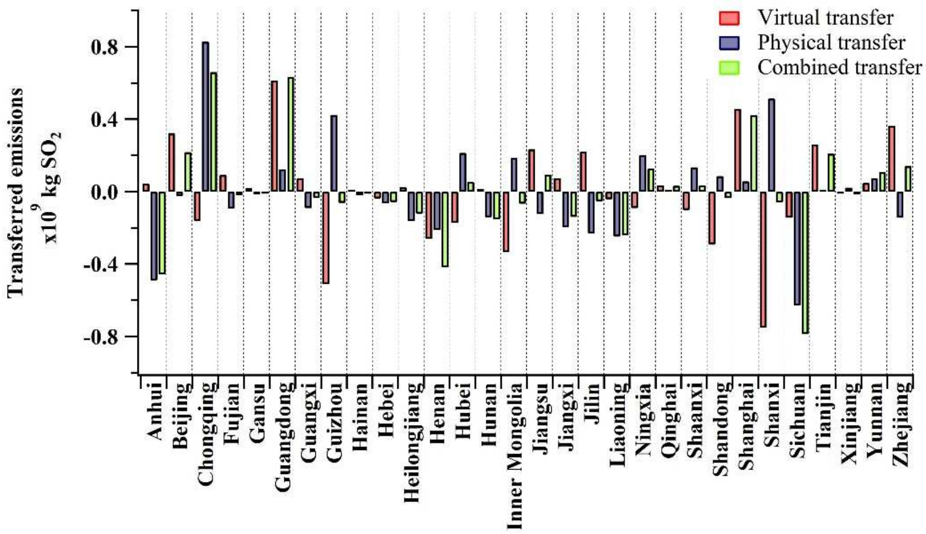

Figure 1 Summary of virtual transfer, physical transfer and combined transfer of SO_2 emissions driven by domestic final use in provinces of China

Inter-Regional Spillover of China's Sulfur Dioxide (SO_2) Pollution across the Supply Chains

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Abstract

Inter-regional spillover of air pollution can be regarded as a mixture of economic externalities and long-distance transport. To comprehensively reveal this problem, a new consumption-based sulfur dioxide (SO_2) emission inventory in 2010 for 30 provincial regions of China was compiled by introducing source-receptor relationship (SRR) model to integrate the spillover impacts of physical transport from emitter (producer) region to receptor region and virtual transfer from driver (consumer) region to emitter region. Compared the emissions induced by final regional demand with the emissions received in seven regions of China, Southern (0.59 Mt), Northern (0.25 Mt), Northwestern (0.18 Mt) and Eastern (0.14 Mt) areas outsourced SO_2 pollution in the mass, whereas Central (-0.66 Mt), Northeastern (-0.42 Mt) and Southwestern (-0.08 Mt) areas took excessive environmental burdens in 2010. The four municipalities, Chongqing, Shanghai, Beijing and Tianjin as well as the most affluent province Guangdong showed significant pollution transfer after an overall assessment of their roles in drivers, emitters and receptors. Shanxi, Inner Mongolia, Guizhou, Henan and Shandong showed the largest co-benefits of SO_2 emissions control for climate change mitigation. Japan was found to receive more portions of transboundary SO_2 deposition than its market shares in China's export instead of other major trade partners of China. As a mega-city, Beijing induced significant SO_2 emissions for power requirement, food consumption, miscellaneous services and her vibrant research activities through the sectors of power industry, coal mining, chemical manufacturing, food-related industries, petroleum processing and coking, but 86% of those emissions were outsourced by Beijing. In total, the spillover of SO_2 emissions induced by Beijing was estimated at 0.20 Mt, 76 times more than its own share as a receptor across the supply chains. This study is competent for an analytic framework of strategic planning for joint prevention and control of air pollution in China and other countries. The results can help reduce pollution transfer, properly tax on drivers, effectively control the emitters, and reasonably compensate the receptors.

Keywords: Pollution transfer; Shared responsibility; Multi-Regional Input-Output (MRIO) analysis; Source-receptor relationship (SRR); Footprint; Consumption-based accounting.

Highlights

- New consumption-based accounting of China's SO_2 emissions to include physical transfer
- Chongqing, Shanghai, Beijing, Tianjin and Guangdong showed significant pollution transfer
- The spillover of SO_2 emissions by Beijing's final demand was 76 times more than its own share
- Japan received excessive transboundary SO_2 deposition than its market shares in China's export
- Data-driven planning of regional compensation and cooperation is highly recommended

1 Introduction

Inter-regional spillover of air pollution can be regarded as a mixture of economic externalities and long-distance transport. Environmental pollution is a typical case for negative externalities in the sense of economics, especially in which air pollution with high diffusibility can influence the air quality in local, regional, and even global scales (Henderson, 1977). The unexpected impacts can be spilled over from the emission origin to the receptor area by long-distance transportation and often with chemical changes (Akimoto, 2003). On the other hand, anthropogenic emissions of air pollutants are accompanied by economic activities driven by private and public sectors. The responsibility or cost of the pollution usually cannot be properly compensated for only by the producers (Ayres and Kneese, 1969). In the UN's sustainable development goals (SDGs), "responsible consumption and production" is one goal to reduce future economic, environmental, and social costs by involving different stakeholders' cooperation across the supply chains (United Nations, 2015). Revealing and responding to the inter-regional spillover of environmental pollution forges China to achieve the SDG goal of responsible consumption and production and the national goal of building a beautiful China.

Understanding the drivers behind direct pollution sources is an enlightening bridge to connect atmospheric science and environmental policy studies. Not like the great efforts on global analyses of greenhouse gas (GHG) emissions (Rogelj et al., 2016) and recent improvement at the city scale (Shan et al., 2018a), there is limited attention paid to emissions of air pollutants in the context beyond local or regional concerns, such as sulfur dioxide (SO_2), nitrogen oxides (NO_x), black carbon (BC), and organic carbon (OC) (Amann et al., 2013), despite there are evident co-benefits from co-control of emissions of GHGs and those critical air pollutants (Li et al., 2018; Watts et al., 2015). Classical research of atmospheric chemistry on air pollution is focused on revealing unheeded mechanism for aggravating air pollution or facilitating extreme pollution events (Sun et al., 2006), and figuring out where those critical primary or secondary air pollutants come from and the roles they play (Song et al., 2006). These findings are fundamental, but not necessarily leading the policy-makers to draw an effective regulation or countermeasure, because the direct behaviors of air pollution are closely linked with various economic activities and incentives in which there might be a trade-off for a society between two different goal-oriented policies. Environmental extended input-output (EEIO) analysis is one of useful tools to quantify the environmental burdens "embodied" in all economic activities, especially in the cross-boundary trade, from the viewpoint of consumer responsibility (Wiedmann and Lenzen, 2018). This kind of consumption-based accounting along with territorial production-based inventory framework are both indispensable to design rational and effective regional policies for China to mitigate climate change (Zhang, 2015) and control air pollution.

There have been several meaningful studies focused on the spillover of carbon dioxide (CO_2) emissions embodied in trade within China. Feng et al. (2013) pointed out there is severe inter-provincial carbon leakage, where less developed provinces produce high-carbon-intensive and low-value-added goods mainly driven by the exports to highly developed coastal provinces in China (Feng et al., 2013). Meng et al. (2013) discussed the change of inter-regional distribution of CO_2 emissions between 2002 and 2007 via global production networks (Meng et al., 2013). Su and Ang (2014) conducted a comprehensive analysis of multi-regional embodied CO_2 emissions in China by combing two different approaches (Su and Ang, 2014). Zhang (2017) compared the spillover effects and feedback effects of CO_2 emissions in Western, Central and Eastern China (Zhang, 2017). Mi et al. (2017) estimated the CO_2 emissions embodied in China's trade and found that the emission flow patterns have changed significantly in both China's domestic and international trade since the global financial crisis in 2007 (Mi et al., 2017).

Compared to air pollutants with complex reaction and heterogeneous spatial distribution, CO_2 is the dominant anthropogenic GHG with a long atmospheric lifetime and global warming impacts (Archer et al., 2009). It is not as significant as air pollutants to discuss the contribution of physical transport of CO_2 to the inter-regional spillover effects. Recent studies combined analyses of consumption-based emissions of air pollutants and pollution transfer from chemical transport modelling are dedicated to quantifying the impacts of air pollution on human health (Brunekreef and Holgate, 2002). The first attempt of great significance was to investigate trans-boundary impacts of China's air pollution on US air quality (Sulfate, CO, BC and Ozone) which was embodied in Sino-US international trade (Lin et al., 2014). Takahashi et al. (2014) estimated consumption-based health impacts from primary BC and

OC in Asian countries by introducing source-receptor relationship (SRR) into consumption-based inventory compilation (Takahashi et al., 2014). Jiang et al. (2015) quantified the health loss due to $PM_{2.5}$-related air pollution embodied in China's export at provincial level by combining production-based inventory, EEIO model, chemical transport model, and exposure-response model for mortality estimation (Jiang et al., 2015). Zhang et al. (2017) conducted a global study on $PM_{2.5}$-related mortality transfer with international trade (Zhang et al., 2017). Increasing literatures contribute to compiling and analyzing multi-regional consumption-based emission inventory, mainly for $PM_{2.5}$ (Table 1).

There remains a sharp gap that sparse effort was put into building a consumption-based SO_2 inventory with consideration of physical transport in spite of indisputable importance of SO_2 pollution damage to ecosystems (Likens et al., 1996) and potential to impel secondary $PM_{2.5}$ formation (Sun et al., 2006). Previous evidence shows that foreign direct investment has little net impact on China's SO_2 emissions due to stringent environmental regulation (Zhao et al., 2018). Additionally, global impacts embodied in China's international trade have been concentrated but the major receptor of these damages is China herself with inequality amongst different provinces (Zhang et al., 2017). In this study, transport effects were taken into account consumption-based analysis of China's SO_2 emissions in 2010 by introducing the SRR transport matrix. This new consumption-based inventory was able to reveal the overall inter-regional spillover of SO_2 pollution influenced by both natural and socio-economic factors. One of the mega-cities in China, Beijing, was further investigated as a case to trace the hot-spots of SO_2 emissions embodied in the transboundary flows of supply chains. The SRR adjusted EE-MRIO model developed in this study is competent for an analytic framework for a data-driven implementation of joint prevention and control of air pollution for China and other developing countries, especially with regard to urgency of regional compensation and cooperation mechanism. The insights into sectoral contribution to the pollution transfer across the supply chains are meaningful to achieve a more efficient and precise regulation plan. It also has referential value for other economies to take real actions together for shared responsibility in air pollution between regional and international consumers and producers, with an eye to damage takers.

Table 1 Selected literatures on multi-regional consumption-based accounting of air pollutants

Observed time	**Covered area**	**Type of air pollutant**	**Physical transport Yes / No**	**Impact evaluation Yes / No**	**Impact indicator**	**Reference**
1997–2010	China and trade partners	$PM_{2.5}$	No	No	n/a	(Guan et al., 2014)
2007	Provinces of China	Mercury	No	No	n/a	(Liang et al., 2014)
2006	China and US	Sulfate, Ozone, BC and CO	**Yes**	**Yes**	Surface concentrations	(Lin et al., 2014)
2008	Countries and regions in Asia	BC and OC	**Yes**	**Yes**	Premature deaths	(Takahashi et al., 2014)
2007	Provinces of China	$PM_{2.5}$	**Yes**	**Yes**	Premature deaths	(Jiang et al., 2015)
2007	Provinces of China	$PM_{2.5}$, SO_2, NO_x and NMVOC	No	No	n/a	(Zhao et al., 2015)
2007	Provinces of China	BC	**Yes**	No	n/a	(Li et al., 2016)
2010	Beijing-Tianjin-Hebei (China)	$PM_{2.5}$, SO_2, NO_x and NMVOC	No	No	n/a	(Zhao et al., 2016)
2002–2007	Provinces of China	SO_2	No	No	n/a	(Liu and Wang, 2017b)
2010	Worldwide	$PM_{2.5}$	No	**Yes**	Disability-adjusted life year losses	(Liang et al., 2017)
2012	Chinese mega cities	BC	No	No	n/a	(Meng et al., 2017)
2005	Asian countries and regions	$PM_{2.5}$ (BC and OC)	**Yes**	**Yes**	Premature deaths	(Nagashima et al., 2017)
2007	Provinces of China	SO_2, NO_x	No	**Yes**	Virtual treatment cost	(Wang et al., 2017a)
2007	China and trade partners	$PM_{2.5}$	**Yes**	**Yes**	Premature deaths	(Wang et al., 2017b)
2007	Worldwide	$PM_{2.5}$	**Yes**	**Yes**	Premature deaths	(Zhang et al., 2017)
2010	Regions of China	$PM_{2.5}$	**Yes**	**Yes**	Premature deaths	(Zhao et al., 2017)
2010-2011	Worldwide	BC	**Yes**	**Yes**	Radiative forcing	(Meng et al., 2018)
2000	Worldwide	PM_{10}	No	**Yes**	Disability-adjusted life year losses	(Xiao et al., 2018)

2 Material and Methods

2.1 MRIO and consumption-based emission inventory

In a multi-regional input-output (MRIO) framework, different regions and sectors are connected based on monetary flows (Miller and Blair, 2009).

$$\begin{pmatrix} \boldsymbol{x^1} \\ \boldsymbol{x^2} \\ \vdots \\ \boldsymbol{x^m} \end{pmatrix} = \begin{pmatrix} \boldsymbol{A^{11}} & \boldsymbol{A^{12}} & \cdots & \boldsymbol{A^{1m}} \\ \boldsymbol{A^{21}} & \boldsymbol{A^{22}} & \cdots & \boldsymbol{A^{2m}} \\ \vdots & \vdots & \ddots & \vdots \\ \boldsymbol{A^{m1}} & \boldsymbol{A^{m2}} & \cdots & \boldsymbol{A^{mm}} \end{pmatrix} \begin{pmatrix} \boldsymbol{x^1} \\ \boldsymbol{x^2} \\ \vdots \\ \boldsymbol{x^m} \end{pmatrix} + \begin{pmatrix} \boldsymbol{f^1} \\ \boldsymbol{f^2} \\ \vdots \\ \boldsymbol{f^m} \end{pmatrix} \quad (1a)$$

$$\boldsymbol{F} = ({f_i}^{st})_{si \times t} = \begin{pmatrix} {f_1}^{11} & {f_1}^{12} & \cdots & {f_1}^{1t} \\ \cdots & \cdots & \cdots & \cdots \\ {f_i}^{11} & {f_i}^{12} & \cdots & {f_i}^{1t} \\ \vdots & \vdots & \cdots & \vdots \\ {f_i}^{s1} & {f_i}^{s2} & \cdots & {f_i}^{st} \end{pmatrix} \quad (1b)$$

As shown in Equation (1a), total output $\boldsymbol{x} = \boldsymbol{Ax} + \boldsymbol{f}$ and $\boldsymbol{x} = (\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{f}$. $\boldsymbol{x^t} = ({x_j}^t)$ denotes the sum of total output of sector *j* in region *t* (consumer, driver region). $\boldsymbol{f^s} = ({f_i}^s)$ represents final demand in which ${f_i}^s = \sum_t {f_i}^{st}$ denotes the sum of final demand in region *t* for the goods produced in sector *i* of region *s* (producer, emitter region). To compare with driving forces in different regions, the vector of final demand $\boldsymbol{f}$ can be reproduced as a matrix $\boldsymbol{F}$ (Equation 1b). $\boldsymbol{A} = (\boldsymbol{A^{st}}) = ({a_{ij}}^{st})$ denotes a normalized matrix of intermediate input, ${a_{ij}}^{st} = {z_{ij}}^{st}/{x_j}^t$ in which ${z_{ij}}^{st}$ denotes the inter-sector monetary flow from sector *i* in region *s* to sector *j* in region *t*.

To calculate the SO_2 emissions embodied in different regions of goods and services $\boldsymbol{E} = (E^{st})_{s \times t}\ or\ ({E_i}^{st})_{si \times t}$, which can be regarded as consumption-based accounting (Peters, 2008), an environmentally extended MRIO (EE-MRIO) model is required by adding production-based SO_2 emission inventory $\boldsymbol{D} = ({D_i}^s)$ with corresponding information of sectors and regions, as shown in Equation (2).

$$\boldsymbol{E} = \widehat{\boldsymbol{D}}\, \widehat{\boldsymbol{x}}^{-1}\, (\boldsymbol{I} - \boldsymbol{A})^{-1}\, \boldsymbol{F} = \widehat{\boldsymbol{d}}\, (\boldsymbol{I} - \boldsymbol{A})^{-1}\, \boldsymbol{F} = \widehat{\boldsymbol{d}}\, \boldsymbol{L}\, \boldsymbol{F} \quad (2)$$

$\boldsymbol{d} = (d_i{}^s) = (D_i{}^s / x_i{}^s)$ denotes region-specific direct SO_2 emissions per unit of total output by each sector. $\boldsymbol{L} = (\boldsymbol{I} - \boldsymbol{A})^{-1}$ represents the Leontief inverse matrix of MRIO model, and $\boldsymbol{L^{st}}$ denotes the sub-matrix of $\boldsymbol{L}$ corresponding to the intermediate input in region *s* for one unit of final demand in region *t*.

$$\boldsymbol{E^{st}} = \sum_{\boldsymbol{n}} \boldsymbol{d^{s'}} \boldsymbol{L^{sn}}\, \boldsymbol{f^{nt}} \tag{3}$$

Equation (3) presents the way to quantify total emissions generated in region *s* across all the pathways of supply chain that is driven by final consumption in region *t*, where *n* denotes the supplying region, or called 'last seller' (Kanemoto et al., 2014) associated with different pathways, and $\boldsymbol{d^{s'}}$ denotes transpose of the vector $\boldsymbol{d^s}$. This basically complies with the concept and MRIO-based accounting of footprints (Fang et al., 2014), like carbon footprint (Davis and Caldeira, 2010) and material footprint (Wiedmann et al., 2015).

$$\boldsymbol{E^{t}_{n=s}} = (\boldsymbol{d^{1'}} \boldsymbol{L^{1s}} + \boldsymbol{d^{2'}} \boldsymbol{L^{2s}} + \cdots + \boldsymbol{d^{m'}} \boldsymbol{L^{ms}})\, \boldsymbol{f^{st}} \tag{4}$$

In parallel, the 'gate-type' consumption-based accounting can be useful if one is interested in the role of last seller (*n*), which is designated as region *s* in Equation (4), in the contribution to embodied emissions. Last seller (Wiedmann et al., 2015), last selling (Kanemoto et al., 2014) or place of last sale (Kanemoto et al., 2011) are adopted terms to represent the direct or embodied flows from the last supplier to the final users, which is a very useful perspective for green supply chain analysis in multi-regional input-output model. In bottom-up practice of life-cycle analysis, the attention to first-tier iteration of upstream emissions was generally focused, because this part of activity data is relatively easy to collect. If one could provide an embodied rather than direct intensity database to correspond to bottom-up activity database, it makes the policy-makers easily trace both direct and indirect environmental impacts without conducting complicated IO modelling by themselves. One of this type of database, "3EID", was developed and widely used for years in Japan (Nansai et al., 2003).

This includes not only the emissions generated in region *s* but also the emissions in other regions accompanying the supplied finished goods in region *s* to final users in region *t* (Liu and Wang, 2017b).

Detailed discussion about the boundaries of these two types of consumption-based accounting on CO_2 emissions in power sector can be found in our previous study (Zhang et al., 2015).

$$\boldsymbol{E}^{s}_{balance} = \boldsymbol{D}^{s} - \boldsymbol{E}^{s} \tag{5}$$

The indicator $\boldsymbol{E}^{s}_{balance}$ of emission balance in region *s* is found in Equation (5) by subtracting consumption-based emissions from production-based emissions, which equals to emissions embodied in import subtracted from emissions embodied in export (Peters and Hertwich, 2008). Here, both import and export consist of interregional transfer and international trade. Emissions embodied in international import were not included as this study mainly focuses on responsibility of Chinese different provinces for interregional spillover within China. The responsibility of production from other countries for air quality of China is minor and beyond the scope of this study.

$$\boldsymbol{E}^{st}_{net(v)} = \boldsymbol{E}^{st} - \boldsymbol{E}^{ts} \tag{6}$$

Equation (6) can be used to discuss the net virtual flow of emissions between two provinces. If $\boldsymbol{E}^{st}_{net(v)} > \boldsymbol{0}$, it means the embodied emissions from region *s* to region *t* exceed the embodied emissions from region *t* to region *s*, which indicates there is net effect of outsourcing from region *t* to region *s* (Liu and Wang, 2017b).

Table 2 Structure of Chinese Multi-Regional Input-Output Tables

		Intermediate Use			**Final Use**						**Total Output**
		Region 1	**…**	**Region m**	**Region 1, FC**	**Region 1, GCF**	**…**	**Region m, FC**	**Region m, GCF**	**Export**	
Intermediate Input	**Region 1**	Z^{11}	…	Z^{1m}	FC^{11}	GCF^{11}	…	FC^{1m}	GCF^{1m}	EX^{1}	X^{1}
	…	…	…	…	…	…	…	…	…	…	…
	Region m	Z^{m1}	…	Z^{mm}	FC^{m1}	GCF^{m1}	…	FC^{mm}	GCF^{mm}	EX^{m}	X^{m}
	Import	IM^{1}	…	IM^{m}	IM^{FC1}	IM^{GCF1}	…	IM^{FCm}	IM^{GCFm}	**0**	
Value-added		V^{1}	…	V^{m}							
Total Input		X^{1}	…	X^{m}							

MRIO tables used in this study are the Chinese 30-sector and 30-province Input-Output tables in 2010 (Figure S1 and Table S1), which were compiled by the Institute of Geography Sciences and Natural Resources Research (Chinese Academy of Sciences) and China's National Bureau of Statistics (Liu et al., 2014). As shown in Table 2, final demand category consists of final consumption expenditure (FC) and gross capital formation (GCF) in each provincial region, and one category for exports (EX). Imports (IM) in the monetary unit are shown in an additional row between domestic intermediate inputs and value-added factors. Details about compilation of MRIO tables can be found in the supporting information of a leading work (Feng et al., 2013).

2.2 Harmonizing sectors of production-based emission inventory with MRIO tables

Production-based SO_2 emission inventory in China is available in the MEIC (Multi-resolution Emission Inventory for China) database (http://www.meicmodel.org/dataset-mix.html), which were provided by the Tsinghua University and its collaborators (Li et al., 2017b), but the sectoral emissions in this inventory need to be harmonized with sectoral economic activities in the MRIO tables to compile the vector of SO_2 emission intensities. Sectoral energy consumption in each provincial region was referred to allocate SO_2 emissions from power, industry, transport, and residential/commercial sources into corresponding industrial sectors and final consumers. Provincial energy consumption statistics were obtained from the CEADs (China Emission Accounts and Datasets) database (http://www.ceads.net/). Raw coal consumption, diesel consumption, and total economic output are the main indicators for allocation of power, industry, transport, commercial and residential sources. Similar harmonizing procedures and formulae can be found in the previous study (Zhang et al., 2015). The sectoral CO_2 emissions by province in 2010 were also obtained from the CEADs database.

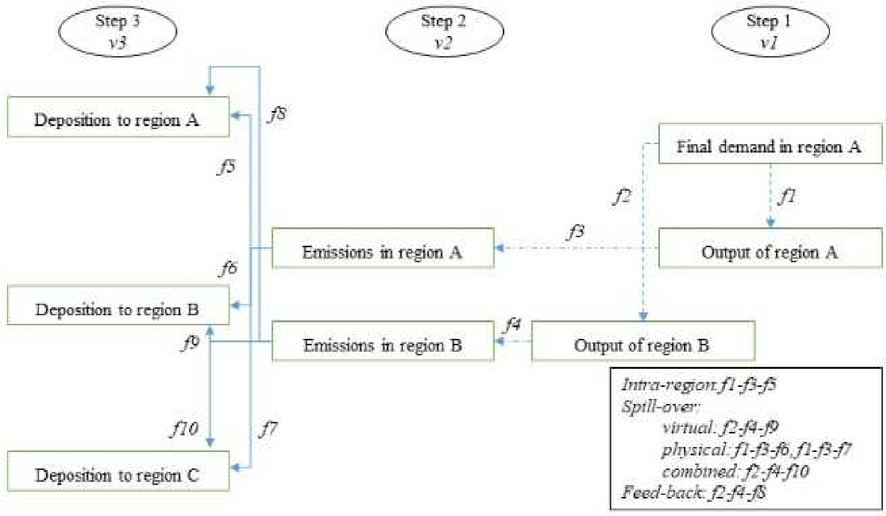

Figure 1 Concept of driver, emitter, and receptor regions of air pollution to link physical transfer with virtual transfer of environmental burdens: *v1* represents the monetary flows and virtual transfer (*f1* and *f2*) between consumers and producers, *v2* represents sectoral pollution intensity (*f3* and *f4*) between production and emissions, *v3* represents the deposition and physical transfer (*f5−f10*) between emitters and damage receptors.

2.3 Transport matrix and source-receptor relationship

Ambient SO_2 can be transported from its emitting origin (source) to the deposition destination (receptor), and SO_2 concentrations in one region reflect not only the local emissions but impacts from atmospheric transport. This physical transfer in terms of yearly averages between source region and receptor region, named source-receptor relationship, is essential to understand location disparity between consumers, producers and receptors (Li et al., 2016). In this work, the deposition module in the RAINS (Regional Air Pollution INformation and Simulation)-Asia model (Arndt et al., 1998) was used to prepare Chinese interregional SO_2 transport matrix. We extracted the gridded modelling data about total sulfur deposition (dry + wet) in this module. The resolution of each grid is 1° × 1° (around 10,000 km^2). It records grid-by-grid total deposition from various origins including more than 100 sub-country regions in Southeast Asia and East Asia as well as other sources like former USSR, volcanoes and international shipping. Because we focus on Chinese emissions, only the deposition originated from Chinese provinces was separated and other sources were grouped as ‘others’ in input data. We compared the code of grids with the geographic boundary of each province to count the grid numbers which were shared with two or more provincial jurisdictions. It helps reduce the double counting by allocating equally among the shared regions. Then we summed up the deposition of grids corresponding to each province to prepare a province-wide source-receptor relationship matrix in terms of SO_2 deposition. The base year is 1995 in this module, so we converted the absolute deposition into relative deposition rate by each origin (province) as a SRR transport matrix. It is because different provinces have different economic growth rates as well as SO_2 emissions that relative contribution from each origin to the receptor region is far less stable over years than long-term variations of meteorological conditions according to some observations (Whiteman et al., 2014).

This SRR transport matrix is not sophisticated as high-resolution models of atmospheric chemical transport, but adequate for policy-makers to identify hot-spots of transboundary SO_2 flows as previous studies demonstrated (Li et al., 2016; Takahashi et al., 2014). Combining the virtual transfer (v_1) between consumers and producers derived from MRIO model, and sectoral SO_2 direct emissions from production-based inventory (v_2) with the SRR transport matrix (v_3) from RAINS-Asia model, the complex relationship among drivers, emitters, and receptors can be figured out to evaluate the trade-offs between physical transfer and virtual transfer of transboundary SO_2 pollution and impel better cooperation on air quality improvement in China (Figure 1).

Consumption-based emission inventory can be integrated with SRR transport matrix as shown in Equations (7)–(9):

$$\boldsymbol{E_{SRR}} = \boldsymbol{C'E^{st}} = \boldsymbol{C'U\,E} = \boldsymbol{C'U\,\hat{d}\,(I-A)^{-1}\,F} \tag{7}$$

$$\boldsymbol{U} = (U_{pq})_{s\times si} = \begin{cases} 1, & q = (p-1)i+1, (p-1)i+2, \dots, pi \\ 0, & else \end{cases} \tag{8}$$

$$\boldsymbol{E_{SRR,t}} = \boldsymbol{C'\widehat{E^{st}}} = \begin{pmatrix} \boldsymbol{E_{SRR,t}}^{\boldsymbol{11}} & \boldsymbol{E_{SRR,t}}^{\boldsymbol{1t}} & \cdots & \boldsymbol{E_{SRR,t}}^{\boldsymbol{1s}} \\ \boldsymbol{E_{SRR,t}}^{\boldsymbol{t1}} & \boldsymbol{E_{SRR,t}}^{\boldsymbol{tt}} & \cdots & \boldsymbol{E_{SRR,t}}^{\boldsymbol{ts}} \\ \vdots & \vdots & \ddots & \vdots \\ \boldsymbol{E_{SRR,t}}^{\boldsymbol{r1}} & \boldsymbol{E_{SRR,t}}^{\boldsymbol{rt}} & \cdots & \boldsymbol{E_{SRR,t}}^{\boldsymbol{rs}} \end{pmatrix}, t = 1,2,3 \dots t \tag{9}$$

$\boldsymbol{E_{SRR,t}} = (\boldsymbol{E_{SRR,t}}^{\boldsymbol{rs}})$ denotes SRR adjusted SO_2 emissions embodied in final demand in region *t*. $\boldsymbol{U} = (U_{pq})_{s\times si}$ with elements of 1 and 0 represents the operation to sum all embodied emissions from one producer region for a certain consumer region, and it diminishes the matrix size of $\boldsymbol{E}$ to comply with the transport matrix $\boldsymbol{C}$ since this model does not differentiate deposition behaviors of sectoral emissions. $\boldsymbol{C} = (c^{sr})$ denotes a normalized SRR transport matrix, representing the proportion of emissions from region *s* deposited on region *r* (receptor region, received deposition impact) to the total emissions generated in region *s*.

Given a case region *t*, the elements of matrix $(\boldsymbol{E_{SRR,t}}^{rs})$ can be grouped into four categories. (I) $\boldsymbol{E_{SRR,t}}^{tt}$ represents the SO_2 emissions deposited to region *t* from the production in region *t* for the final demand in region *t*. There is no concern of transboundary pollution. (II) $\boldsymbol{E_{SRR,t}}^{rt}$ $(\mathbf{r} \neq \mathbf{t})$ represents the SO_2 emissions deposited to the region other than *t* from the production in region *t* for the final demand in region *t*. Production is local, but emitted SO_2 is spilled into other regions by the processes of physical transfer. (III) $\boldsymbol{E_{SRR,t}}^{rs}$ $(\mathbf{r}, \mathbf{s} \neq \mathbf{t})$ represents the SO_2 emissions deposited onto the region other than *t* from the production outside region *t* for the final demand in region *t*. Transboundary pollution is influenced by both processes of virtual transfer and physical transfer, which is the most complicated. (IV) $\boldsymbol{E_{SRR,t}}^{ts}$ $(\mathbf{s} \neq \mathbf{t})$ represents the SO_2 emissions deposited onto the region *t* from the production outside region *t* for the final demand in region *t*. Production is outsourced but pollution is transferred back to the consumer (driver region). To count the responsibility of driver region, inter-regional spillover of pollution occurs in the category (II) and (III), and the feedback pollution (negative spillover) occurs in the category (IV).

Similar to Equation (6), the net physical transfer and combined transfer flows of SO_2 emissions could be defined as Equation (10) and Equation (11):

$$\boldsymbol{E^{rs}_{net(p)}} = \sum_{\boldsymbol{t}} \boldsymbol{E_{SRR,t}}^{\boldsymbol{rs}} - \sum_{\boldsymbol{t}} \boldsymbol{E_{SRR,t}}^{\boldsymbol{sr}} \qquad (10)$$

$$\boldsymbol{E^{rt}_{net(v+p)}} = \sum_{\boldsymbol{s}} \boldsymbol{E_{SRR,t}}^{\boldsymbol{rs}} - \sum_{\boldsymbol{s}} \boldsymbol{E_{SRR,r}}^{\boldsymbol{ts}} \qquad (11)$$

3 Results

3.1 Consumption-based accounting of SO_2 emissions by province of China

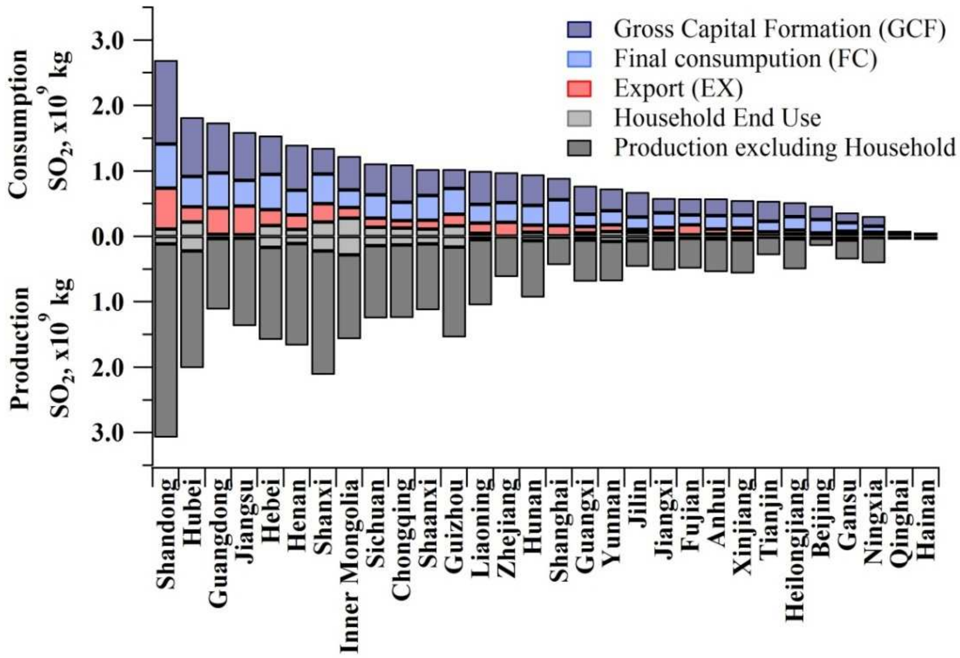

Figure 2 Consumption-based SO_2 emissions compared with production-based emissions by province of China

This study provides a consumption-based SO_2 emission inventory by province of China in 2010. The categories of final demand include final consumption (FC) and gross capital formation (GCF) in each provincial area of mainland China (except Tibet for insufficient data) and total export (EX). Figure 2 shows SO_2 emissions induced by FC, GCF, or EX in each province in descending order, compared with production-based MEIC emission inventory (Li et al., 2017b) in a reverse vertical axis. SO_2 emissions allocated from energy end-use by household are shown separately in each province. The countrywide SO_2 emissions induced by FC, GCF, and EX were estimated at 8.6 Mt (30%), 12.7 Mt (45%) and 4.7 Mt (17%), with additional 2.3 Mt (8%) from household direct use, consisting of total 28.4 Mt emissions in 2010. The percentage error was 0.5% between this consumption-based inventory and original production-based inventory in MEIC. Emissions induced by GCF in most provinces are larger than inducement by FC of the same province, except one mega-city Shanghai and some less-developed provinces in Western China like Guizhou and Qinghai. Shandong was the province of the largest induced SO_2 emissions (2.7 Mt, 9.5% of total emissions), followed by Hubei (1.8 Mt, 6.3%), Guangdong (1.7 Mt, 6.0%), Jiangsu (1.6 Mt, 5.6%) and Hebei (1.5 Mt, 5.3%), *etc.*, which suggests strong economic linkages between these driving provinces and other regions, especially from the massive capital investment. Three provinces with advanced manufacturing industries show extraordinary SO_2 emissions embodied in export for foreign final users, say, Shandong (0.63 Mt, 13.4% of emissions embodied in export), Jiangsu (0.44 Mt, 9.3%) and Guangdong (0.40 Mt, 8.5%). Note that emissions embodied in international export should not be accounted for the 'footprint' of SO_2 for China but this portion of emissions was estimated by a consistent consumption-based accounting method and used in the further discussion to differentiate from the emission responsibility for domestic consumption.

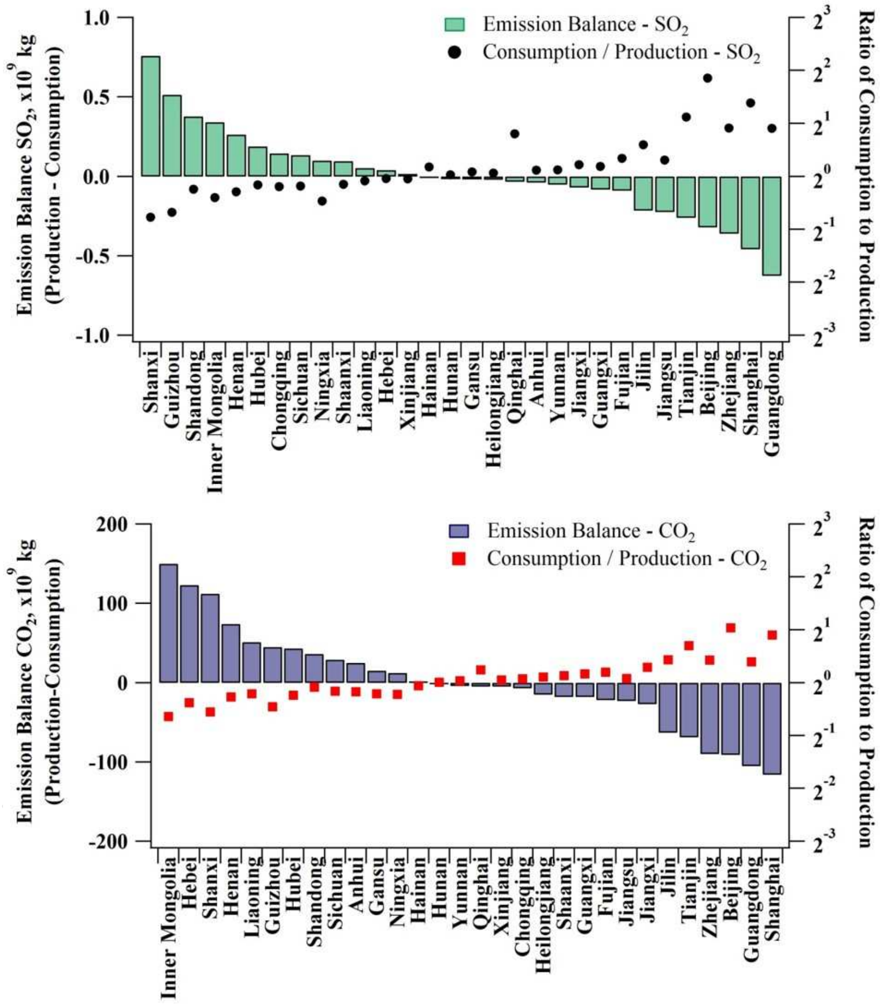

Figure 3 Emission balances of SO_2 and CO_2 between production-based and consumption-based emissions for domestic consumption by province of China

Significant differences exist in some provinces between production-based and consumption-based SO_2 emissions for domestic consumption. The emission balance based on Equation (5) by province is shown as Figure 3. Production-based emissions for domestic consumption were estimated by subtracting emissions embodied in international export from original production-based emissions by province, and consumption-based emissions for domestic consumption consist of emissions embodied in FC and GCF in each province. This indicator of emission balance can purely reflect the interregional (interprovincial) virtual transfer of SO_2 emissions within China. The five provinces with the largest positive emission balance were Shanxi, Guizhou, Shandong, Inner Mongolia and Henan, which means production emissions in one province for domestic consumption exceed countrywide emissions induced by final demand of that province, vice versa. The main source of positive emission balance should come from vibrant power industry and manufacturing sectors in those provinces (Zhang et al., 2016). Guangdong, Shanghai, Zhejiang, Beijing and Tianjin were the top five provinces with the largest negative emission balance. All of these five provincial regions are the most developed areas in China. Guangdong was the biggest driver of China's SO_2 emissions since it shows the largest negative emission balance with leading induced emissions. If one considers the relative importance of induced emissions, the megacity Beijing became the first in terms of the ratio of consumption-based emissions to production-based emissions, and the second was another megacity Shanghai. It proves the importance of this study, revealing remarkable spillover of SO_2 emissions between less-developed (inland) and the most developed (coastal) areas associated with East-to-West industrial upgrading processes in China (Feng et al., 2013).

Figure 3 also shows the revisited emission balance of CO_2 based on CEADs database (Shan et al., 2018b). The five provinces with the largest positive emission balance were Inner Mongolia, Hebei, Shanxi, Henan and Liaoning; whereas Shanghai, Guangdong, Beijing, Zhejiang and Tianjin were the top five beneficiaries. These regions with the largest negative CO_2 emission balance were the same as SO_2 emission balance, indicating those five provincial regions should take more responsibility to transfer green technology or financial aids to support the cleaner production in other less-developed regions in China. Combining the ranks of SO_2 emission balances with the ranks of CO_2 emission balances, Shanxi should be given first priority to reduce air pollution in accordance with mitigation of GHG emissions. The following hot spots were found to be Inner Mongolia, Guizhou, Henan and Shandong. Previous study reported that Shandong, Shanxi, Inner Mongolia and Guizhou, *etc.* are the regions with high co-benefits of CO_2 mitigation (Dong et al., 2015), which demonstrates high potential and benefits to implement win-win environmental polies for joint control of air pollution and GHG emissions in these areas.

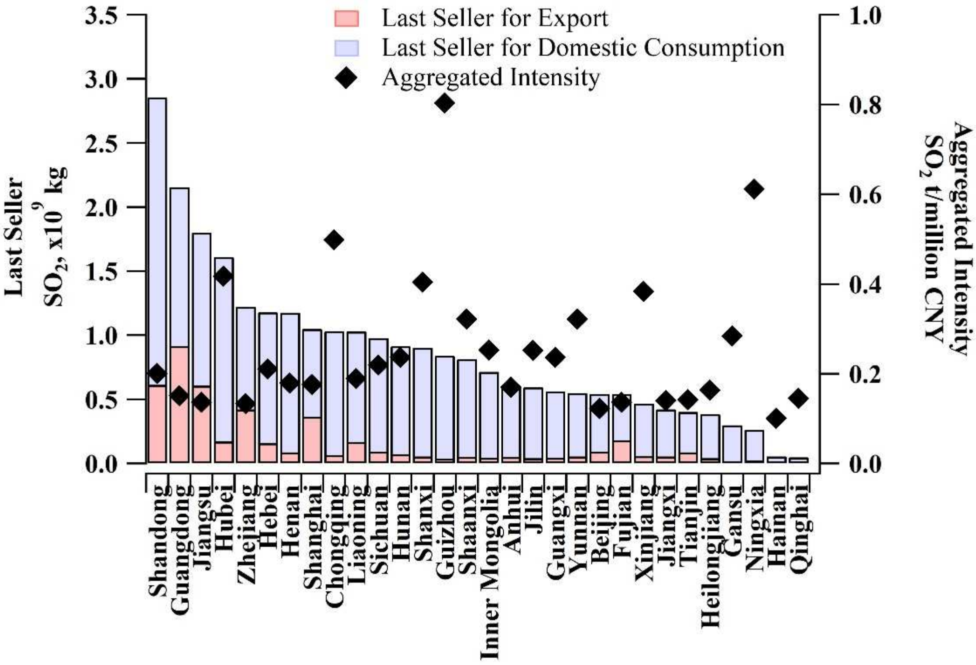

Figure 4 Consumption-based SO_2 emissions allocated by last seller and aggregated intensity of finished goods by province of China

Figure 4 shows another perspective of consumption-based accounting for the contribution from last seller across the supply chains. The five provinces associated with the largest embodied emissions as a last seller were Shandong, Guangdong, Jiangsu, Hubei and Zhejiang, in which four provinces except Hubei had significant emissions embodied in export. There is a clear different purpose or advantage in analyzing final consumer or last seller. If one wants to figure out the consumption-based emissions, he needs to analyze the final consumer, but to what extent the induced emissions are transmitted and interacted between sectors and regions, the analysis of last seller is one of approaches to decompose these impacts. In this context, there were the largest SO_2 emissions embodied in export from finished goods in Guangdong (Figure 4) whilst Shandong emitted the most SO_2 responsible for the export

(Figure 2). This is meaningful for policy-makers or the importers of finished goods to figure out life-cycle upstream emissions of those products from the last seller, similar to the concept of cradle-to-gate emissions by product in regional life-cycle assessment (Yang and Heijungs, 2017). The aggregated intensities of finished goods by region equal to emissions associated with last seller divided by the regional output. Integrated with emission pattern and economic structure, this index could be used to compare the enablers of green supply chains in different provinces. The supply chains in Guizhou, Ningxia and Chongqing were the dirtiest in terms of SO_2 emissions, whereas the enablers of green supply chains in top five last sellers were following Zhejiang ≈ Jiangsu > Guangdong > Shandong > Hubei. This breakdown approach advocates a shared responsibility of air pollution across the supply chains (Gallego and Lenzen, 2005), because there generally were significant interprovincial emissions embodied in the immediate inputs. Since the impact of SO_2 emissions is more geographically sensitive than carbon dioxide emissions, the burdens of physical transfer combined with virtual transfer among different regions is separately addressed hereafter.

3.2 Drivers, emitters and receptors of SO_2 emissions by province of China

One of the highlights of this study is able to differentiate and track sectoral China's SO_2 emission flows among driver, emitter and receptor regions. By introducing Equations (7)–(11) into this SRR adjusted EE-MRIO model, this work linked quantitative estimation of virtual transfer with physical transfer to better deliver policy implications for SO_2 pollution control in China. Figure 5 shows SO_2 emissions received in receptor region from emitter region in China. To simplified the results, all the provinces were classed into seven regions, named Northern (N), Northeastern (NE), Northwestern (NW), Eastern (E), Central (C), Southwestern (SW) and Southern (S) China. From the perspective of receptor region, Eastern China bore the largest environmental burdens (5.2 Mt SO_2), 64.8% from itself, but also significantly from Northern (10.1%) and Central (16.8%) China. Central China was estimated to receive 4.8 Mt SO_2, in which 60.2% of emissions were from itself, followed by Southwestern (12.6%), Eastern (9.4%) and Northern (7.6%) China. More than one third of SO_2 emissions (0.74 Mt) received in Northeastern China were found from the Northern areas, whereas only 0.10 Mt SO_2 received in Northern China came from Northeastern China (3.0%). Northwestern China (10.7%) was the largest contributor to emissions received in North China except itself (73.5%). Notably, 91.8% of SO_2 emissions from Southwestern China would not spread beyond it, indicating that more local concerns may be required in this region, but later we found that there exist numerous transfers between provinces within this region.

It is worth nothing that Japan received 1.3 Mt SO_2, equivalent to 4.5% of total China's SO_2 emissions which is almost half of all the emissions deposited on the land outside China. However, Japan only accounted for 6.16% of market share of China's export (World Bank, 2018). It received more deposition impacts than other major trade partners of China, like United States and Germany, *etc*. There are minor percentage differences of regional contribution in terms of total emissions or export-driven emissions, but the three largest emitter regions ranked as Eastern, Northern, and Central China, say, Shandong (E, 0.24 Mt), Shanxi (N, 0.12 Mt), and Henan (C, 0.10 Mt). Note that the differences were counted in terms of all the final demand categories or only taking export into account the induced deposition. East China takes relatively more responsibility than other regions for Japan in terms of export-driven emissions. We suggest Japan provide more technology and financial support to East China areas to deepen the cooperation with China in cleaning air quality.

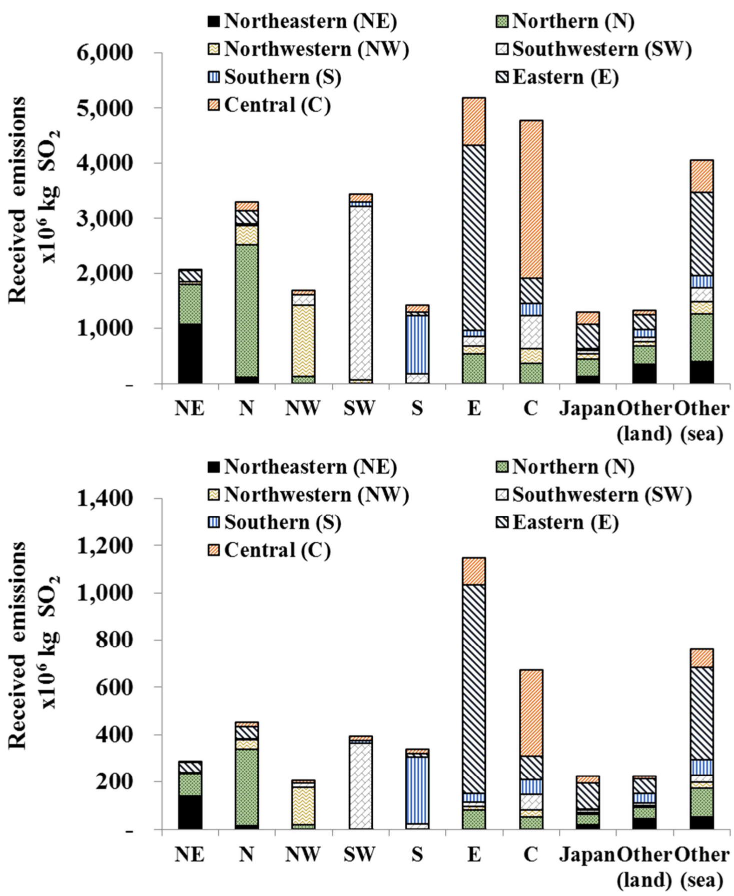

Figure 5 SO_2 emissions received in receptor region from emitter region in China in terms of total emissions (upper) or emissions driven by export (lower)

Figure 6 shows the relationship between driver region and receptor region, which combines the effects of virtual transfer from driver region to emitter region and physical transfer from emitter region to receptor region. Final regional demand in Eastern China including final consumption and gross capital formation was found to be the largest driver in terms of China's SO_2 emissions, followed by the export, final demands in Northern and Central China. Export-driven emissions contributed significantly to the deposition in all the regions, especially in Southern China (25.0%) and Eastern China (23.6%). Compared the emissions induced by final regional demand with the emissions received in each region, the net combined transfer among seven regions of China revealed unbalanced responsibility between drivers and receptors, in which Southern (0.59 Mt), Northern (0.25 Mt), Northwestern (0.18 Mt) and Eastern (0.14 Mt) areas were beneficiary of outsourcing SO_2 pollution in the mass, while Central (-0.66 Mt), Northeastern (-0.42 Mt) and Southwestern (-0.08 Mt) areas lost this gaming with additional environmental burdens.

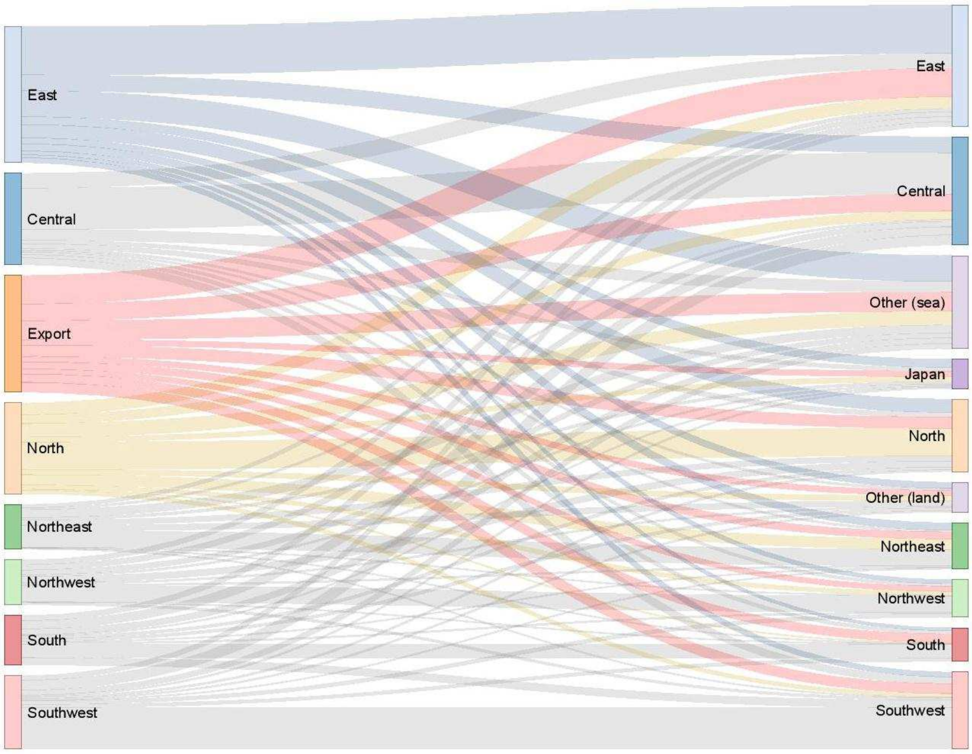

Figure 6 Interaction between driver region (left) and receptor region (right) in terms of combined physical and virtual transfer of SO_2 emissions in China

More information can be found in Figure 7 and Figure S2 for province-by-province comparison of net physical transfer and net combined transfer of SO_2 emissions. Colors in bars denote different driving forces in the supply chains. The total net effects of physical transfer include emission balances driven by domestic final use, export, and additional deposition proportional to emissions from household direct use by each region (Figure 7). Chongqing (SW) and Guizhou (SW) showed large positive physical transfer of SO_2 emissions, and Sichuan (SW) showed the largest negative physical transfer, whereas there was only limited spillover in Southwestern China (Figure 5). This indicated that significant emissions from Chongqing (SW) and Guizhou (SW) deposited onto Sichuan (SW), which means unbalanced responsibility within Southwest China should be adjusted. With an eye to consumer responsibility, large benefits of physical transfer in Shanxi (N) turned out to be slightly negative in combined transfer (Figure 7 and Figure 8), suggesting that Shanxi (N) is a bottleneck for SO_2 pollution control but should not be overly criticized in the context of industrial division in China, similarly observed in Guizhou (SW). Regarding the categories of final regional demand, GCF generally played a more important role in net combined transfer than FC, but these two drivers did not necessarily show the same direction all the time (Figure S2). The combined transfer driven by FC and GCF in Hebei (N) were positive (0.10 Mt) and significant negative (-0.67 Mt), respectively. Similar results were found in Gansu (NW) and Shanxi (N), which indicated that the deterioration of air quality in these regions was dominated by the capital investment rather than final regional demand from both household and the government.

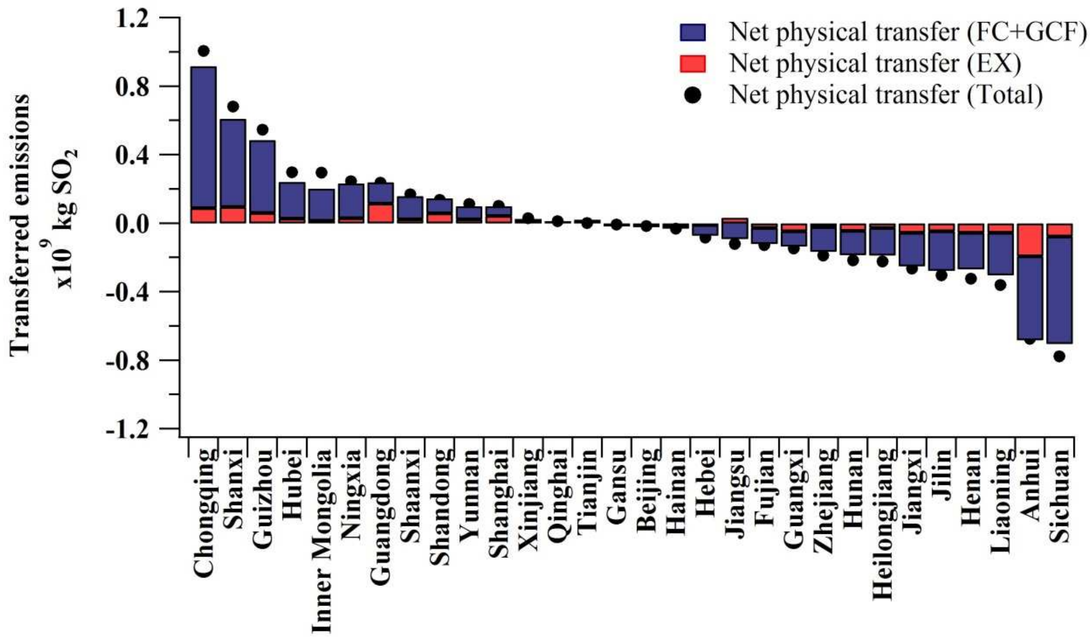

Figure 7 Net physical transfer of SO_2 emissions by emitter region in China

Figure 8 summarizes the evaluation of virtual transfer, physical transfer and combined transfer of SO_2 emissions by province of China. The presented results here only include the driving forces of FC and GCF to focus on interacted and shared responsibility amongst 30 Chinese provinces in this study, since the impacts of international export and deposition outside those provinces have been discussed hereinbefore. Chongqing (SW), Guangdong (S), Shanghai (E), Beijing (N) and Tianjin (N) showed large amount of net combined SO_2 transfer. They are four municipalities plus the most affluent province in China, demonstrating indisputable pollution transfer in these developed regions after an overall assessment of their roles in drivers, emitters and receptors. Chongqing mainly benefited from physical transfer while Guangdong and Shanghai received more favors from virtual transfer. Sichuan (SW), Anhui (E), Henan (C), Liaoning (NE) and Hunan (C) significantly showed negative combined SO_2 transfer, where regional compensation mechanism should be fairly considered for joint control of

SO_2 pollution. Sichuan and Henan both suffered from negative virtual transfer and physical transfer, while Anhui, Liaoning and Hunan mainly received damages from physical transfer. The negative physical transfer in Jiangsu and Zhejiang partially offset their significant environmental benefits from outsourcing production, whereas Beijing and Tianjin received much smaller negative influences.

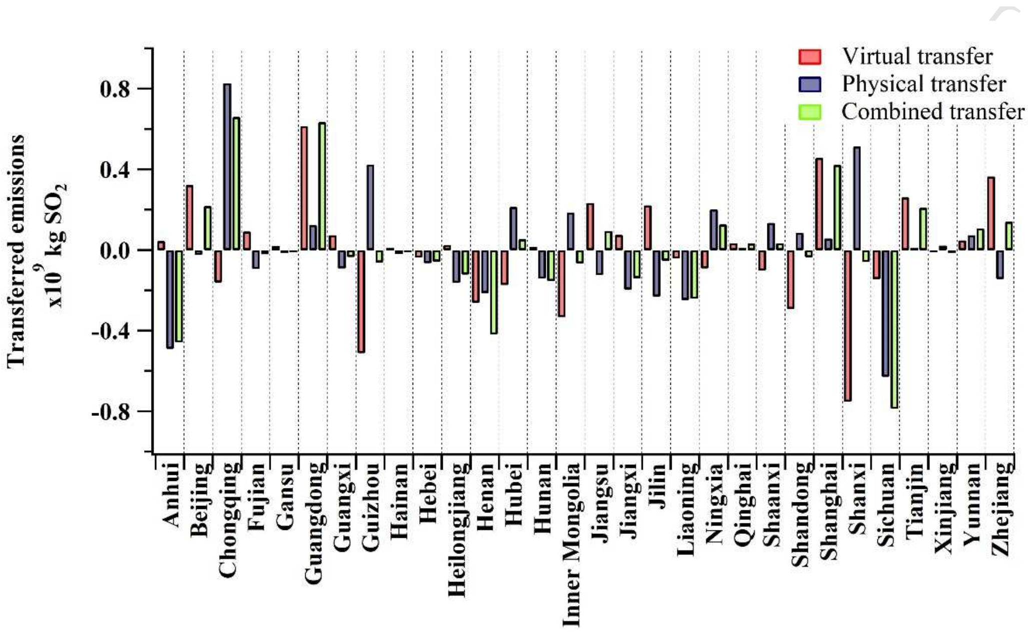

Figure 8 Summary of virtual transfer, physical transfer and combined transfer of SO_2 emissions driven by domestic final use in provinces of China

3.3 Spillover of SO_2 emissions associated with final consumption of Beijing

A detailed sector-by-sector case study on spillover of SO_2 pollution was focused on Beijing. Beijing, as the political, cultural and scientific center of China, intentionally reduced economic dependence on heavy manufacturing and turned to service-driven growth strategy for years, resulting in the highest ratio between consumption-based emissions and production-based emissions (Figure 3). However, it is unclear that how significance of the spillover and feedback effects of air pollution (SO_2 emissions as an example) are driven by final consumption of Beijing. As shown in Figure 9, Beijing induced 204,000 t SO_2 mainly for miscellaneous services ("2-Other Services", 46.3%), food-related consumption ("2-Food Production", "2-Agriculture" and "2-Catering", 18.3% totaled), electricity and heat consumption ("2-Power Industry", 14.3%). As a scientific hub of China, research activities ("2-Research", 6.3%) were found to be the fourth largest contributor in terms of 12,800 t SO_2 emissions for Beijing. Power industry, coal mining and chemical manufacturing were the largest three upstream sources for emissions embodied in scientific research activities and other services.

As shown in Figure 10, the sectors of power industry, coal mining, chemicals, food-related industries as well as petroleum processing and coking generated most of SO_2 emissions for Beijing's final consumption, however, 86% of those emissions occurred outside Beijing. More than half of SO_2 emissions of power generation for Beijing were from Shanxi (N) and Inner Mongolia (N). Emissions of coal mining significantly came from Shanxi (N) and Hebei (N). Emissions of chemical manufacturing were mainly from Hebei (N), Jiangsu (E), Shandong (E) and Beijing (N). Shanxi (N), Shaanxi (NW), Xinjiang (NW) and Inner Mongolia (N) were responsible for emissions of petroleum processing and coking. Emissions in food related sectors were not outsourced as much as other sectors, as 38% of emissions came from agriculture and food production in Beijing.

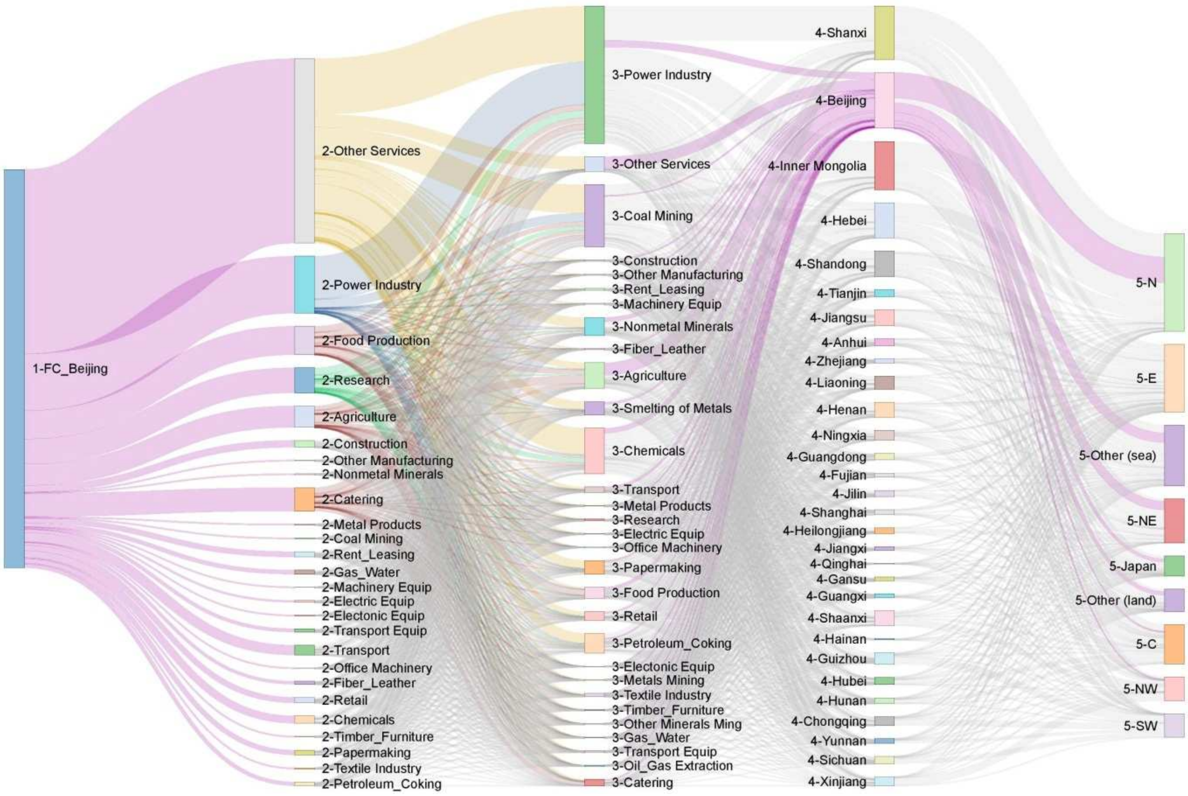

Figure 9 Interacted flows of SO_2 emissions driven by final consumption of Beijing. The columns from the left to the right denote SO_2 emissions which were induced by final consumption of Beijing (1), decomposed by the category of consumed finished goods (2), the emitting industrial sector (3), the emission generated region (4), and the destination of deposition (5), respectively

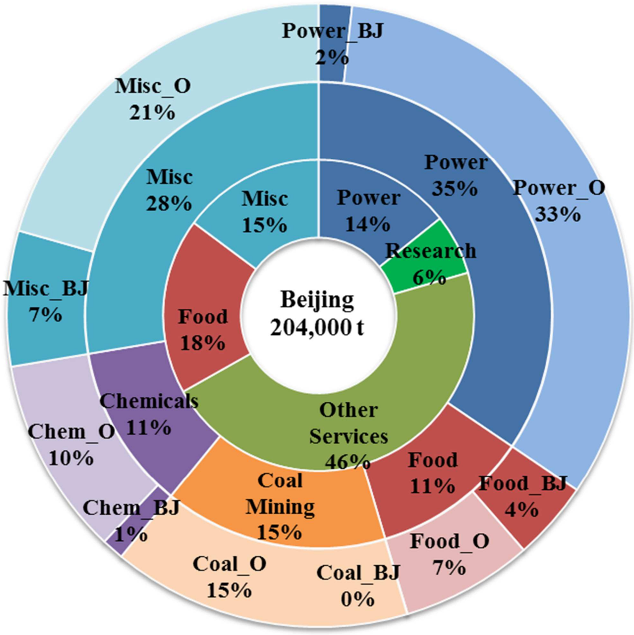

Figure 10 Major contributors in terms of SO_2 emissions embodied in finished goods (inner), generated sectors (middle) and outsourced portions (outer); BJ: Beijing, O: Other regions, Chem: Chemicals, Misc: Miscellaneous

Table 3 Spillover and feedback effects of SO_2 emissions induced by final consumption of Beijing, (I) no transboundary effects, (II) only physical transfer, (III) combined transfer (including virtual transfer), (IV) feedback effect

Unit: 1,000 t

Receptor \ Emitter	Beijing	Other regions
Beijing	(I) 2.6	(IV) 1.3
Other regions	(II) 26.1	(III) 174.7

The impacts of spillover may be severer than the awareness of local government and the inhabitants. Table 3 summarizes the spillover and feedback effects of SO_2 emissions induced by final consumption of Beijing, and detailed provincial contribution can be referred in Table S2. Basically this study includes two parts to analyze the spillover of environmental burdens amongst regions: the first is to reallocate production-based SO_2 emissions into consumer regions and sectors to estimate virtual transfer, and the second is to extend the trace of these reallocated emissions to damage-receptor regions for quantifying physical transfer (Figure 1). Emissions from Beijing mainly deposited onto Hebei (N), Liaoning (NE) and Beijing (N), but there was more significant deposition on Eastern and Central China by upstream emissions across the supply chains for final consumption in Beijing (Table S2). If we focus on Beijing's productivity for her own final consumption, the responsible emissions deposited to Beijing were only 2,563 t (I), but ten times emissions from Beijing deposited onto other regions (II), of which most went to her surrounding provinces. Resulting from physical transfer, this is not taken into account economic spillover effects in previous framework (Zhang, 2017). If the upstream emissions were included, it became six times larger than the own emissions of Beijing. The spillover of SO_2 emissions induced by Beijing was estimated at 0.20 Mt in total (II+III), 76 times more than its own share as a receptor (2,563 t) across the supply chains. Significant transboundary paths for final demand in Beijing included 6,002 t SO_2 deposited to Northeast China from emissions generated in Inner Mongolia (N), 3,609 t SO_2 to Central China from Shanxi (N) and 2,489 t SO_2 to East China from Hebei (N), *etc*. There was additional deposition (1,272 t) equivalent to the half of local generation, which has been outsourced to other regions but reversely returned to Beijing as a feedback effect (IV), mainly from Hebei (493 t), Inner Mongolia (311 t), and Shanxi (297 t). To strengthen the environmental regulation, the joint control of SO_2 emissions in those three provinces surrounding Beijing is of the highest importance, not only for air quality in Beijing or North China, but also beneficial to improving the air quality in Northwestern, Central and Eastern areas based on our findings.

4 Discussion

The SRR adjusted EE-MRIO model developed in this study is competent for an analytic framework to deepen the communications between scientists and policy-makers for a data-driven implementation of joint prevention and control of air pollution for China. Shared responsibility should become a consensus between consumers (driver region) and producers (emitter region), with an eye to damage takers (receptor region) due to the externality (Zhang, 2017). The quota or target of emission abatement need be carefully designed to properly tax on drivers, effectively control the emitters, and reasonably compensate the receptors. The decision making by Chinese central government ought to maximize the mechanism of bottom-up feedback and interregional negotiation based on quantitative evidences. Liu and Wang (2017b) pointed out the reasonable emission reduction plans should reduce pollution leakage in interprovincial trade, and the developed provinces should provide financial and technical support for pollution control in less developed regions, because some pollution-intensive industries in developed provinces have migrated to less developed provinces where there are higher emission intensity and lower marginal treatment cost (Liu and Wang, 2017b). Compared to their studies, this study integrated the assessment of receptor role into EE-MRIO model which is an attempt to partially internalize pollution externality by taking physical transfer into account. Due to data limitation, previous study assumed the same sulfur content in all sectors of one province (Liu and Wang, 2015), but this study improved the allocation method by using different indicators of energy consumption between groups of sectors (Zhang et al., 2015). Based on this modelling, Sichuan (SW), Anhui (E), Henan (C), Liaoning (NE) and Hunan (C) could be prior to conducting interprovincial ecological compensation for their significant burdens in terms of negative combined SO_2 transfer. Especially the negotiation and cooperation on joint prevention and control of SO_2 pollution should be promoted in Southwestern China between the beneficiaries Chongqing (SW), Guizhou (SW) and the damage receptor Sichuan (SW) of the same region.

Regarding the transboundary SO_2 pollution between China and Japan, we argue that Japan received much more portion of transboundary deposition than its market share in China's export instead of other major trade partners of China, like United States and Germany, though they can also receive long-distance secondary impacts (Lin et al., 2014; Nagashima et al., 2017). The supply chain paths around agriculture in China were found to have the greatest health impact in terms of $PM_{2.5}$ (Nagashima et al., 2017), and this study on Beijing revealed the high importance of food-related industries across the supply chains for SO_2 pollution. China and Japan are the near neighbors with deep economic ties, who have mutual incentive to accelerate international cooperation to improve regional air quality.

There remain two limitations in this study. One is the lagging data-set for policy-making. Though the version in 2010 is our latest available Chinese MRIO tables, SO_2 emissions have clearly reduced during the past decade and the hot spots of SO_2 loading shrank to much smaller areas with the center of Hebei (N)and Henan (C) provinces (Li et al., 2017a). But it is still useful that this study reveals the necessity of joint prevention and control actions in Beijing-Tianjin-Hebei areas to include Hernan (C), Shandong (E) and Liaoning (NE) provinces, especially for there is evident that the capital investment mainly in construction sector has increased the SO_2 emissions (Liu and Wang, 2017a). Another limitation is lack of further evaluation on impacts of secondary formation during the transport and deposition. The introduced SRR matrix was efficient to discuss contribution from primary emission sources, while secondary emissions and impacts need comprehensive chemical transport models to evaluate (Lin et al., 2014).

5 Conclusions

In this study, a new SRR adjusted consumption-based SO_2 emission inventory in 2010 for 30 provincial regions of China was compiled to integrate the spillover impacts of physical transport from emitter region to receptor region and virtual transfer from driver region to emitter region. It can help the policy-makers to plan a data-driven implementation of joint prevention and control of air pollution for China. Compared the emissions induced by final regional demand with the emissions received in each region, the net combined transfer among seven regions of China revealed that Southern (0.59 Mt), Northern (0.25 Mt), Northwestern (0.18 Mt) and Eastern (0.14 Mt) areas outsourced SO_2 pollution in the mass, whereas Central (-0.66 Mt), Northeastern (-0.42 Mt) and Southwestern (-0.08 Mt) areas took excessive environmental burdens in 2010. The four municipalities, Chongqing (SW), Shanghai (E), Beijing (N) and Tianjin (N) as well as the most affluent province Guangdong (S) showed significant pollution transfer after an overall assessment of their roles in drivers, emitters and receptors. Sichuan (SW), Anhui (E), Henan (C), Liaoning (NE) and Hunan (C) were found negative combined SO_2 transfer, where regional compensation and cooperation in prevention and control of SO_2 emissions should be impelled with those developed beneficiaries. Shanxi (N), Inner Mongolia (N), Guizhou (SW), Henan (C) and Shandong (E) showed the largest potential benefits to co-control SO_2 emissions and GHG emissions. Japan received more portions of transboundary SO_2 deposition than its market shares in China's export, which has mutual incentive together with China to deepen international cooperation to improve regional air quality in Asia.

Significant interregional spillover of SO_2 emissions was found driven by final consumption in Beijing. Power requirement and food consumption are significant drivers for SO_2 emissions induced by Beijing, as well as her vibrant research activities. The power industry, coal mining, chemical manufacturing, food-related industries and petroleum processing and coking generated most of SO_2 emissions, but 86% of those emissions were outsourced by Beijing. In total, the spillover of SO_2 emissions induced by Beijing was estimated at around 0.20 Mt, 76 times than its own share as a receptor across the supply chains. Additional deposition equivalent to half of local generation were found to have been outsourced to other regions but reversely returned to Beijing as a feedback effect.

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