Letter

Imbalanced transfer of trade-related air pollution mortality in China

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Keywords: interprovincial trade in China, PM\textsubscript{2.5} related mortality, value added, imbalance transfer

Supplementary material for this article is available online

Abstract

Revealing the determinants and associated impacts of the transboundary pollution caused by trade is a critical issue when promoting the joint control among regions. This interdisciplinary study utilizes physical, economic and epidemiological methods to explore the anthropogenic PM\textsubscript{2.5} related mortality driven by interprovincial trade within China and its determinants. The results showed that 68% of the mortality flow in China was from the central and north plain area, with 29% occurring within these regions and 39% flowing to other eastern and western provinces. The high death intensity resulting from higher exports of heavily polluted agricultural and heavy industry products dominated the trade surplus of PM\textsubscript{2.5} mortality for the central and northern plains of China; these bring an imbalanced economic return for these regions, with only 43% of the value added generated in interprovincial trade being retained in these regions. Our study provides a more comprehensive picture of how atmospheric pollution deaths were caused by domestic trade within China, which may facilitate the multilateral pollution mitigation actions from an environmentally economic balanced perspective.

1. Introduction

The recent rapid economic development and urbanization in China were accompanied by abundant energy consumption and severe atmospheric pollution. After China entered the world trade organization, estimation show that its population-weighted fine particular matter (PM\textsubscript{2.5}) concentration almost doubled, from 36.0 µg m\textsuperscript{-3} in 1990 to 63.5 µg m\textsuperscript{-3} in 2005, resulting in more than one million lives lost annually [1]. Although the Chinese government released its toughest-ever Air Pollution Prevention and Control Action Plan (hereafter, Action Plan) in 2013, China’s population-weighted PM\textsubscript{2.5} concentration is still far more than the WHO’s PM\textsubscript{2.5} guideline value of 10 µg m\textsuperscript{-3}, especially in the populous central and eastern coastal regions [2].

Transboundary pollution transport is one of the issues of concern in pollution mitigation actions, as it is related to pollution attribution and joint control action between regions. Recently, in addition to pollution attribution from a production-based perspective, pollution redistribution through product trade has attracted increasing attentions, as it may lead to broader cross-regional impact and even undermine the pollution mitigation efforts due to the disparities in pollution control efficiency among the trade partners [3–11]. For example, Zhang et al [3] compared the PM\textsubscript{2.5} related health impacts caused by physical transportation and product trade in 10 regions globally, and the results shown that 22% of global PM\textsubscript{2.5} related pollution deaths were associated with consumption in another region linked by international trade, which is far more than the effect from atmospheric transportation (12% of total). As the ‘world’s factory’, 12% of China’s PM\textsubscript{2.5} pollution deaths can be attributed to international exports [12]. Given the prominence of interprovincial trade within
China, Zhao et al [8] explored PM$_{2.5}$ pollution and the associated health impact caused by interprovincial trade, and the results showed that product trade aggravated the premature deaths transferred from the north and east coast to the central region. These studies indicated the globalization of air pollution, but treat regional total trade flow or its consumption as a whole and fail to distinguish the impact caused by specific regions or sectors, hindering further pollution mitigation from trade perspective.

Economic development and trade are the underlying driving force of product trade, and the boom in various environmental problems in recent years has raised wide discussion on the environment–economy trade-off for product trade [13–16]. Based on previous pollutant-specific analysis of trade’s impact, Zhang et al [13, 14] used atmospheric pollutant equivalents (APE) as a representation of typical pollutants (including sulfur dioxide, nitrogen oxides, soot and dust) and quantified the unbalanced exchange of gross domestic production (GDP) and pollution embodied in trade between provinces. However, atmospheric pollution is a result of the combined physical and chemical reactions of various pollutants under certain geographical and meteorological conditions. The same amount of pollutants and same composition would exert diverse pollution impacts in different regions due to disparities in environmental capacity and population density; data on these impacts have been a critical reference used by regions to balance their industrial production and urban planning [17]. Therefore, to some extent, a pollutant-based analysis cannot fully represent the actual impact caused by trade.

Our study coupled four physical, economic, and epidemiological models and used PM$_{2.5}$ related premature deaths as an indicator to calculate the air pollution impact driven by interprovincial trade within China. We then used the index decomposition analysis to reveal the underlying determinants of unequal exchange among regions. Finally, to provide a comprehensive assessment of trade and its associated impact, we compared the value added (also known as GDP) and pollution deaths attributable to trade for each province. PM$_{2.5}$ related premature death is chosen as a measure because protecting the public health is the ultimate goal of pollution mitigation; and it is a combined result of pollutant emissions, meteorological conditions and population density.

2. Methodology and data

2.1. Estimation of anthropogenic PM$_{2.5}$-related premature deaths
Satellite-based ground-level PM$_{2.5}$ mass concentrations and the integrated exposure response (IER) model from GBD 2010 were combined to estimate PM$_{2.5}$-related premature deaths. Satellite-based ground-level PM$_{2.5}$ concentrations provide relatively more accurate information on the scale and spatial distribution of exposure. The data used here were obtained from our previous study [18], and they were estimated by using the aerosol optical depth (AOD) derived from satellite instruments (MODIS and MISR onboard the Terra satellite) and conversion factors between AOD and PM$_{2.5}$ simulated by the GEOS-Chem chemical transport model (version 3.5). The utilized emissions were derived from Multiresolution Emission Inventory of China (MEIC: http://www.meicmodel.org/), and emission out of China were derived from the MIX inventory developed by Li et al [19].

The IER model was developed by Burnett et al [20]. It is one of the most popular models for describing the concentration – response relationship between PM$_{2.5}$ and premature deaths for various leading causes. Following previous studies [8, 12, 21], we focus on four leading causes: ischemic heart disease (IHD), stroke, chronic obstructive pulmonary disease (COPD) and lung cancer (LC). These health endpoints share the same equation, but with different parameters. Their relative risk (RR) can be calculated as:

$$RR(C) = \begin{cases} 1 + \alpha \left(1 - e^{-\gamma(C-C_0)}\right), & \text{if } C > C_0 \\ 1, & \text{else} \end{cases}$$

where $C$ is the annual mean PM$_{2.5}$ concentration in 2012; $C_0$ is the counterfactual concentration; $\alpha$, $\gamma$, and $\delta$ are the parameters used to describe the shape of the concentration–response curve. A set of fit parameters those represent the median IER results given by Lee et al (2015) were used in this study, and were shown in table S1.

The mortality attributable to PM$_{2.5}$ exposure can be estimated as:

$$M = \frac{RR - 1}{RR} \times B \times P$$

where $B$ is the death incidence of a given health effect derived from the national average data in GBD2013 [22]; $P$ is the size of the exposed population derived from the LandScan global population database [23]; and $\frac{RR - 1}{RR}$ is the attributable fraction to PM$_{2.5}$ exposure.

Emissions driven by trade are related to anthropogenic activity, so the mortality increase caused by natural source emissions was excluded in this study. To accomplish this, we modeled two scenarios by using the GEOS-Chem model to extract the fraction of PM$_{2.5}$ pollutions stemming from anthropogenic emissions: one with all emissions as inputs and the other without anthropogenic emissions. Furthermore, we assume a linear relationship between the proportion of total mortality to the proportions of total PM$_{2.5}$ concentration. Anthropogenic PM$_{2.5}$ related premature deaths can be calculated as:
where \( M^{\text{anth}} \) is the premature deaths related to \( \text{PM}_{2.5} \) for only anthropogenic emissions; \( C_{\text{all}} \) is the annual mean \( \text{PM}_{2.5} \) concentrations from the scenario with all emissions turned on; \( C_{\text{no, anth}} \) is the annual mean \( \text{PM}_{2.5} \) concentrations from the scenario without anthropogenic emissions. The estimates of \( \text{PM}_{2.5} \) related mortality was conducted at grid cells, and the result for individual grid were summed to derive regional or national total impact (\( M^{\text{tot, anth}} \)).

### 2.2. \( \text{PM}_{2.5} \) pollution deaths attribution to production regions and sectors

Regional \( \text{PM}_{2.5} \) exposure can result from both local emissions and inflows from the surrounding area through atmospheric transportation, and regional emissions can affect pollution exposure and associated health impacts in both local and other regions. Here, we use the nested version of GEOS-Chem (version 3.5) and its adjoint model to attribute national \( \text{PM}_{2.5} \) related pollution deaths to the source region and sectors, as it can simulate the sensitivity or contribution of many sources in a single simulation. The GEOS-Chem adjoint model is combined with the IER model [21], and was simulated over East Asia (11 °S-55 °N, 70 °E-150 °E) at a horizontal resolution of 0.5° × 0.667° to calculate the sensitivity of location- and species-specific emissions to \( \text{PM}_{2.5} \)-related premature deaths in the target regions. A semi-normalized sensitivity was calculated as:

\[
SS^i_k = \frac{\partial M^{\text{tot, anth}}}{\partial e^i_k} \times e^i_k
\]

where \( M^{\text{tot, anth}} \) is regional total \( \text{PM}_{2.5} \) related premature deaths calculated in section 2.1, also names the cost function; \( \frac{\partial M^{\text{tot, anth}}}{\partial e^i_k} \) is the partial derivative of the cost function for anthropogenic emissions in grid \( i \) within the domain and captures the sensitivity of premature death to the emission of species \( k \) in grid \( i \) (\( e^i_k \)).

To minimize the effects of the nonlinear relationship between emissions and pollutant concentrations and between concentrations and mortality, a normalized SS (hereafter \( P \)), which represents the percentage contribution of source-specific emissions to premature deaths, was calculated as:

\[
P^i_k = \frac{SS^i_k}{\sum_i \sum_k SS^i_k} \times 100\%
\]

Furthermore, the contribution of the production-based emissions of sector \( t \) to \( \text{PM}_{2.5} \) related deaths can be calculated as:

\[
M^t = M^{\text{tot, anth}} \times \sum_i \sum_k \left( P^i_k \times \frac{e^i_k}{e^i_{k,t}} \right)
\]

where \( e^i_{k,t} \) represents the emission of species \( k \) in grid \( i \) from sector \( t \). Here \( M^t \) includes mortality occurring locally and in surrounding areas resulting from the emissions of sector \( t \). In the later sections, mortality embodied in export of a given region captures the mortality caused by export nationally, and does not merely refer to mortality occurring only in the export regions.

In the abovementioned model, the anthropogenic emissions of \( \text{PM}_{2.5} \) and its precursor gases including \( \text{NH}_3 \), \( \text{SO}_2 \), \( \text{NO}_x \), \( \text{BC} \), \( \text{OC} \) are considered [24]. Additionally, to promote the accuracy of the simulation, we divide the mainland China into seven regions according to their meteorological conditions (figure S1) (available online at stacks.iop.org/ERL/15/094009/mmedia), and used them as receptor region; accordingly, a total of seven groups of GEOS-Chem adjoint model simulations were conducted, one group for each receptor region. In response to the increased computation load, the simulations of four typical months (January, April, July and October of 2012) from four seasons separately were utilized to represent the year average.

### 2.3. \( \text{PM}_{2.5} \)-related mortality embodied in interprovincial trade within China

The multiregional input-output table (MRIO) integrates the complex material exchange among sectors and regions, and enable us to capture the cumulative impact driven by trade. In the past few years, the MRIO model has been widely used to calculate various environmental pressures (e.g. energy use, \( \text{CO}_2 \) emissions and water use) caused by trade. Here we use the latest noncompetitive 30-province, 30-sector MRIO table for China compiled by Mi et al [25] to attribute production-based pollution deaths to the consumption regions. The monetary balance of MRIO can be shown as:

\[
\begin{pmatrix}
X^1 \\
X^2 \\
X^3 \\
\vdots \\
X^m
\end{pmatrix} = \begin{pmatrix}
\mathbf{A}^{1,1} & \mathbf{A}^{1,2} & \cdots & \mathbf{A}^{1,m} \\
\mathbf{A}^{2,1} & \mathbf{A}^{2,2} & \cdots & \mathbf{A}^{2,m} \\
\mathbf{A}^{3,1} & \mathbf{A}^{3,2} & \cdots & \mathbf{A}^{3,m} \\
\vdots & \vdots & \ddots & \vdots \\
\mathbf{A}^{m,1} & \mathbf{A}^{m,2} & \cdots & \mathbf{A}^{m,m}
\end{pmatrix} \times \begin{pmatrix}
\mathbf{y}^1 \\
\mathbf{y}^2 \\
\mathbf{y}^3 \\
\vdots \\
\mathbf{y}^m
\end{pmatrix}
\]

where \( \mathbf{x} \) is a vector of the total economic output of region \( r \) by sector; \( \mathbf{y}_{r,s} \) is the final demand vector by sector produced in region \( r \) and consumed in region \( s \); \( \mathbf{A}_{r,s} \) is a normalized matrix of intermediate coefficients, representing the input from sectors in region \( r \) required to produce one unit of output from each sector in region \( s \).
Under this framework, pollution deaths embodied in the sector specific consumption of region \( r \) by source is calculated as follows:

\[
\mathbf{e}^s = \mathbf{f}^r (\mathbf{I} - \mathbf{A})^{-1} \mathbf{y}^s \tag{8}
\]

where \( \mathbf{e}^s \) is a vector capturing the sector specific pollutant emission flow from region \( r \) to region \( s \); \((\mathbf{I} - \mathbf{A})^{-1} \) is the Leontief inverse matrix; \( \mathbf{y}^s \) is the final demand vector for region \( s \); \( \mathbf{f}^r = \mathbf{M}_r / X_r \) is the vector of PM\(_{2.5}\) related pollution death intensity for region \( r \), and data for other regions are zeros; \( \wedge \) represents the diagonalization. Note that the sector specific PM\(_{2.5}\) related pollution deaths of region \( r \) (\( \mathbf{M}_r \)) infers to the total mortality occurring locally and in surrounding areas attributed to PM\(_{2.5}\) pollution generated by the production emissions of each sector from region \( r \).

Value added generated by product trade can be calculated as:

\[
\mathbf{v}^s = \tilde{\mathbf{v}} (\mathbf{I} - \mathbf{A})^{-1} \mathbf{y}^s \tag{9}
\]

\( \mathbf{v}^s = \mathbf{V}^s / X_r \) is the vector of value added generated by per unit output by sector for region \( r \), \( \mathbf{V}^s \) is derived from the MRIO table and consists of employee compensation, net taxes on production, depreciation of fixed capital and operating surplus.

**2.4. Index decomposition analysis**

Index decomposition analysis (IDA) is one of the major techniques used to disaggregate the contribution of various determinant factors to the total change in a research object. It has been widely used to isolate the contribution of various social and technical factors to changes in environmental pressure between time points, e.g. CO\(_2\) emissions [26, 27], air pollutants [28, 29] and water pollution [30]. In 2013, Jacob and Marschinski [31] extended it and use it to investigate the contributions of four indicators (trade balance, economy-wide energy intensity, economy-wide carbon intensity of energy, and trade specialization) to the net flow of CO\(_2\) among countries. Based on an emission embodied in bilateral trade (EEBT) accounting method, in 2015, Jiang et al [32] conducted a similar decomposition to isolate the contribution of these factors to the net carbon flows among provinces within China. To provide consistency with our previous research [8], in this research we employ the MRIO based accounting method, and conduct a similar decomposition to attribute the net flow of PM\(_{2.5}\) related premature death to three factors (economy-wide PM\(_{2.5}\) pollution death intensity, trade balance and trade specialization). In addition, MRIO-based analysis can avoid the double counting when attributing a relative effect to a given region [33]. The energy related index was omitted in this study as there are abundance pollutant emissions were from nonenergy sources. For example, 93% of the NH\(_3\) emissions were from agricultural activities, as fertilizer use and animal husbandry. Regional production related premature deaths driven by other regions can be written as:

\[
\text{MEX}_r = \left( \frac{\mathbf{M}_r}{X_r} \right) \cdot \left( \frac{\mathbf{EX}_r}{X_r} \right) \cdot \text{EX}_r = \text{MI}_r \cdot \mathbf{sp}_r \cdot \text{EX}_r \tag{10}
\]

where \( \mathbf{M}_r \) is the premature deaths induced by the production of region \( r \); \( X_r \) is the total output of region \( r \); and \( \text{EX}_r \) is the output of region \( r \) driven by consumption in other regions. Correspondingly, \( \text{MI}_r \) is the PM\(_{2.5}\) pollution death intensity; \( \mathbf{sp}_r \) is the degree of pollution death from the specialization of exports in region \( r \), and \( \mathbf{sp}_r > 1 \) means region \( r \) is specialized in export in pollution-intensive product, \( \mathbf{sp}_r < 1 \) indicates an opposite situation.

In contrast, the PM\(_{2.5}\)-related premature death inflow of region \( r \) can be written as:

\[
\text{MIX}_r = \left( \frac{\mathbf{M}_r}{X_r} \right) \cdot \left( \frac{\text{MIX}_r}{X_r} \right) \cdot \text{IM}_r = \text{MI}_r \cdot \mathbf{sp}_r \cdot \text{IM}_r \tag{11}
\]

where \( c/r \) means national without region \( r \). Then the net export of region \( r \) was written as:

\[
\text{MEX}_r - \text{MIX}_r = \text{MI}_r \cdot \mathbf{sp}_r \cdot \text{EX}_r - \text{MI}_r \cdot \mathbf{sp}_r \cdot \text{IM}_r \tag{12}
\]

Like Jakob and Marschinski [31], we use the additive refined Laspeyres index decomposition approach proposed by Sun [34], which can distribute the total net flow to various involved factors completely and without residual terms.

**2.5. Uncertainty analysis**

Our research is subject to a number of uncertainties, due to the inherited limitations and assumptions of the models used in above sections. To improve the accuracy, we chose the latest and state-of-the-art models in our study to improve the accuracy as much as possible. A detailed description of the uncertainty and limitations of the models is presented in the supplementary material. As a comprehensive uncertainty analysis combining all affecting factors above is impossible due to the limitations from the computational loads, especially for this study adopting region- and sector-specific perspectives. Thus, the uncertainty ranges shown in the main text only represent the uncertainties in the IER function, which is obtained by running 1000 sets of IER parameters fitted by Burnett et al [20] to calculate the possible distribution of regional pollution deaths.

**3. Results**

**3.1. PM\(_{2.5}\) pollution mortality attributed to interprovincial trade**

In 2012, PM\(_{2.5}\) pollution arising from anthropogenic production and consumption activities contributed 1.08 (95% 95%CI: 0.69–1.30) million premature
Figure 1. PM$_{2.5}$-related mortality embodied in interprovincial exports and imports by provinces (a) and the detailed mortality flows across provinces (b). In panel (a), the regions in shaded red act as net importers, while those shaded blue are means net exporters. In panel b, provinces were ordered from the largest net exporter on the top/left to the largest net importer on the bottom/right.

Deaths in China. As estimated, 27% of these (288,746 deaths [95% CI: 184,301–349,435]) can be attributed to interprovincial trade within China, more than two times that driven by international exports (12%; figure S2).

Regions in China experienced different effects from trade due to the huge diversity in production and pollution control technology, as well as their position in the domestic supply chain. Figure 1(a) compares regional production-related PM$_{2.5}$ health.
impacts driven by consumption in other provinces (namely, interprovincial exports) and those generated by other provinces for producing their consumed goods or services (interprovincial imports); regions in shaded red indicate regions that act as net exporters, while those in blue indicate net exporters. As figure 1(a) shows, regions of net exporters are mainly concentrated in central China (including Anhui, Hunan, Jiangxi and Jiangsu), in the northern plains (including Henan and Hebei), and in some northwestern energy industry provinces (Shanxi and Inner Mongolia). As estimated, the mortality embodied in exports from these regions reached 196,061 (95% CI: 125,142–237,269), which is 1.6 times that embodied in their imports. Notably, Henan, Anhui, Hebei, Hunan and Jiangsu had shown not only the largest exporters but also relatively larger importers compared to the net import regions, because these regions are the most populous provinces in China. While they export to support consumption in other provinces, they also need to import abundant materials and products to support local consumption and economic development. Scaling down the virtual mortality inflows to the province, we can find that the dominant inflows of these net export regions happened to between themselves (upper-left of figure 1(b)), which accounted for 68% of their imports on average, ranging from 61% in Guizhou to 74% in Jiangxi. The largest flow was observed from Anhui to Jiangsu, accounting for 17% of the total outflow from Anhui.

The net importers were mainly concentrated in the developed east coast and some other western or northeastern provinces (figure 1(a)). Their virtual mortality imports were comparable to these net export regions, but those embodied in their exports were relatively small and could only partly offset the imports. As estimated, PM$_{2.5}$ related mortality embodied in their imports reaches 1.8 times that embodied in their exports, with regional variation ranging from 1.1 in Fujian to 5.8 in Hainan. Their imports were dominated by the leading export regions, including Henan, Anhui, Hebei and Jiangsu (upper-right corner of figure 1(b)), which accounted for 45% of their inflows, on average. However, their export-related mortality was evenly distributed over the country with no significant hotspots (lower part of figure 1(b)).

3.2. Determinants of the net flows for regional virtual air pollution mortality

Regional trade pattern of PM$_{2.5}$-related mortality (net inflow or outflow) was a combined result of the mortality embodied in region’s exports and those embodied in their imports, originating from the disparity in trade volume and death intensity between exported and imported product. Figure 2 decomposes the net flow of regional PM$_{2.5}$-related mortality into three determinant factors: economy-wide trade balance, trade specialization and the gap in deaths intensity between the trade partners. Here, trade balance refers to the net export volume in trade; trade specialization shows the PM$_{2.5}$-related mortality content of a region’s export compared to that of regional average, and deaths intensity means the PM$_{2.5}$-related mortality caused when producing unit output.

In figure 2, provinces were ordered from the greatest net exporter on the left to the greatest net importer on the right. For the net export regions (left side of figure 2), their (high) premature deaths intensity plays a positive role in almost all regions (except Jiangsu); it represented 43%–183% of their net exports (−209% for Jiangsu), indicating a large gap in production related heath impacts per unit output existed between these regions and their trade partners. Trade specialization (in pollution-death intensive products) aggravated the trade balance in most of the net export regions, especially for Henan, which exhibited trade specialization with almost all of its trade partners (figure S3). As estimated, the effect from trade specialization (77% of its net export) of Henan even outweighed the contribution from death intensity (43%), making Henan the biggest net exporter, even though it runs a trade deficit. A similar situation can be observed in Hunan, Shanxi, Guizhou and Inner Mongolia. Among the net export regions, Jiangsu showed a rather different pattern; it gains negative impacts from (low) pollution intensity and trade specialization, but its massive trade surplus with almost all trade partners counteracted these negative effects. As estimated, the product output in Jiangsu driven by its interprovincial exports was 2 times that driven by imports, which were generated by other domestic regions.

Compared to the net export regions, the determinant factors were relatively more diverse for the net import regions (right side of figure 2). We can further split these regions into two groups according to their determinant factors. For the net import regions those located in eastern China, their net imports were dominated by their (low) pollution deaths intensity and/or trade specialization. In Zhejiang, for example, the (low) death intensity and trade specialization accounted for 50% and 83% of its net imports, respectively, which largely offset the opposite effect from its trade surplus (−33%), making Zhejiang a leading net importer. For Shandong, its specialized import of pollution death intensive products is the sole negative factor (−285%), and largely counteracted the positive effect from trade surplus (64%) and high death intensity (121%). For the less developed western regions, including Yunnan, Xinjiang, Shaanxi and Guangxi, their net imports were dominated by their trade deficits. In Shaanxi, for example, the nationwide output generated by its import reaches 1.6 times that of its exports, which contributed 256% of its net import for PM$_{2.5}$-related mortality and largely offsetting the opposite
effect from (high) death intensity (−93%) and trade specialization (72%).

3.3. Imbalance of pollution mortality and economic gain across provinces
The diversity in trade volume, trade structure, and economic return per unit output can also bring disproportionate economic returns among regions. Figure 3 compares the net flows of mortality versus value added driven by interprovincial trade for the 30 provinces, and it divides provinces into four groups. Figure 4 separately presents the detailed mortality and value added caused by regional exports and imports by sector; due to the complex trade interactions among sectors and regions when using MRIO analysis, the export- and import-related mortality and value added of a given region were traced back to the source production sectors.

As shown in figure 3, provinces located in the first quadrant (including Zhejiang, Beijing, Shanghai, Liaoning and Fujian) were the largest beneficiaries, as they can outsource pollution related health impacts to other regions while retaining value-added inflows through trade. Provinces in this group used to have a relatively lower healthy burden per GDP in exports due to their high ratios in the export of high-tech and service products, which typically have higher economic returns with lower emissions discharge [15]. Taking Beijing and Shanghai as an example, 75% and 72% of the inflow value added can be sourced back to the equipment and service sectors, respectively, which is almost 2.5 times that of the remaining provinces; while for export related mortality, these sectors only accounted for 15% and 11% of the respective total in Beijing and Shanghai (figures 4(a) and (b)).

In contrast, provinces located in the third quadrant (including Ningxia, Inner Mongolia, Guizhou and Shanxi) are found to be the losers in trade, as they generated more pollution death but little value-added gains than their trade partners. This can be attributed to their higher death burden per unit of GDP as well as their specialization in importing less-polluted products (figure 2). As estimated, the average mortality per GDP generated by exports from this group was 2 times that of their imports. Their relatively low import death intensity can be attributed to their higher imports from the less-polluting service and equipment sectors in other regions; and these two sectors accounted for 23% and 16% of the total value added generated in the supply chain of their imports, respectively (figure 4(d)).

Provinces located in the second and fourth quadrants represented the medium state shaped by various trade flows with other regions: provinces in the fourth quadrant produced more environmental losses by exporting abundant pollution-intensive products, but generated relatively higher economic returns; the opposite situation occurred for provinces in the second quadrant. Notably, regions in group IV share similar health burdens per generated unit of GDP with those of group III, and the slight advantage of provinces in group IV may be that the equipment sector accounted for a relatively higher proportion of their exports (figure 4(b)). This distinction is particularly relevant for Jiangsu—a highly developed east coast province characterized by high-tech equipment manufacturing, and its export-related value added

Figure 2. Decomposition of net exports of embodied pollution deaths for each province. Provinces were ordered from the largest net exporter on the left to the largest net importer on the right.
generated by equipment accounted for 25% of the total (figure 4(b)).

4. Discussion and policy implications

Atmospheric pollution is a global issue due to the complex atmosphere and socioeconomic feedback among regions, and pollution redistribution through trade even exceeds the effect from atmospheric transport. Our study coupled four state-of-the-art models, and attributed pollution to regions and even detailed trade flows among provinces in China. We further revealed the determination of virtual mortality flows among regions by using the IDA.

Our results showed that the central and northern plains in China (including Anhui, Jiangsu, Henan, Hebei, Hunan, Hubei, Jiangxi, Guizhou, Chongqing, Inner Mongolia, Shanxi) are net exporters of virtual mortality, and 57% of their outflows were driven by consumption in the east coast and western China; hence, a trade-based joint control action is urgently needed, especially between the developed east coast regions and these net export regions. Production and control technology transfer indeed are the most effective strategies, and have been widely proposed [7, 35, 36]. Giving the widely existing of competition among industries and regions, which would hinder further cooperation to some extent, hence the central government should set up some agencies or formulate relative policies to promote the technology transfer, and mitigate the air pollution and related impact from a national perspective. Those effective policies aimed at reducing greenhouse gases emission may be introduced in air pollution mitigation action, such as Clean Development Mechanism (CDM), emission trade system and so on. Additionally, previous studies have shown that intermediate product trade from the central to east coast dominated the emission flows, and these intermediate products were always pollution intensive and were further processed into finished products in the import regions [9]. These produce a chance to explore a cross-regional management system such as ecolabeling to promote cooperation between up- and downstream enterprises to reduce emissions along the supply chains efficiently. Moreover, in addition to the trade with east coast provinces, mortality flows between these net export regions themselves were also significant (43% of their total). As these net exporters are always be populous developing regions, and they are experiencing rapid industrialization and urbanization, their production and interregional trade flows are expected to grow in the near future, which would be a new driving force for pollution and the associated impact of central China, thus a joint control action among these regions is also necessary. This to some extent proves the rationality of strengthening the comprehensive pollution reduction action among the 2 + 26 cities scattered in Beijing, Tianjin, Hebei, Shandong, Henan and Shanxi, but the inclusion of Anhui should also be
considered in this control plan due to its higher emission and frequent interaction with existing members.

As the IDA analysis showed, higher pollution-related intensity determined the net outflows of the net export regions (43%–183% of respective total); for most, their mortality intensity amounted to 2 times the national average, which is far more than that of the developed east coast provinces. This ultimately brought the unbalanced environmental losses and economic returns to these regions in trade (figure 3). To improve their environment–economic efficiency, the net export regions should put more effort into the pollution-intensive agriculture and heavy industry sectors (including chemical, metal and nonmetal sectors); this is particularly for Henan, Hunan, Anhui, Hebei and Jiangsu, for which the mentioned sectors contributed for 75%–80% of their respective total deaths embodied in exports, but only accounted for 30%–44% of the valued added. The high health burden of the agriculture sector is due to its high NH₃ emissions from fertilizer use and animal husbandry (93% of national total [29]), which play the dominant role in forming ammonium sulfate and nitrate [37]. Currently, there is no mandatory action to reduce NH₃ emissions because it is difficult to monitor. With ever-increasing control costs

Figure 4. Regional export- and import-related mortality and value added by source sectors. In panels (a) and (b), regional export-related mortality or value added by sector shows the sector in which the original emission-related mortality was induced or the value added was captured. In panels (c) and (d), regional consumption related mortality and value added were traced back to the original sectors but not to the detailed regions. Pie charts above the bars represent group-average sectoral composition under various situations.
from industrial sectors, exploring feasible NH₃ control measures would be more cost-effective [38, 39]. Heavy industry in central and west China are always located downstream in the national supply chain, and the fragmentation of production in China tends to increase the intermediate trade from central to eastern coastal China [40]. Extending their production chain to promote industrial upgrading should be a top priority right now. In 2015, the central government implemented the “One Belt, One Road” initiative, which requires abundant products and services to equip central Asia and this may provide an opportunity for the central and western China. The local government should create more attractive investment condition to introduce more advanced enterprises to upgrade their low-end industries, and strive to be upstream of the upcoming economic community, final to reach an environmental and economic balanced develop pattern.

Data availability

The data that support the findings of this study are available upon reasonable request from the authors.

Acknowledgments

This study was supported by the National Science Foundation of China (71904097 and 41625020), National Postdoctoral Program for Innovative Talent (BX20180164), and Chinese Postdoctoral Science Foundation (2019M650712).

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