Environmental Science and Ecotechnology 16 (2023) 100264

Contents lists available at ScienceDirect

Environmental Science and Ecotechnology

journal homepage: www.journals.elsevier.com/environmental-science-and-ecotechnology/

Original Research

Air pollution health burden embodied in China's supply chains

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ARTICLE INFO

Article history:
Received 13 September 2022
Received in revised form
6 March 2023
Accepted 13 March 2023

Keywords:
China
Air pollution
Mortality
Trade
Supply chain

ABSTRACT

Product trade plays an increasing role in relocating production and the associated air pollution impact among sectors and regions. While a comprehensive depiction of atmospheric pollution redistribution through trade chains is missing, which may hinder targeted clean air cooperation among sectors and regions. Here, we combined five state-of-the-art models from physics, economy, and epidemiology to track the anthropogenic fine particle matters ($PM_{2.5}$) related premature mortality along the supply chains within China in 2017. Our results highlight the key sectors that affect $PM_{2.5}$-related mortality from both production and consumption perspectives. The consumption-based effects from food, light industry, equipment, construction, and services sectors, caused 2–22 times higher deaths than those from a production perspective and totally contributed 63% of the national total. From a cross-boundary perspective, 25.7% of China's $PM_{2.5}$-related deaths were caused by interprovincial trade, with the largest transfer occurring from the central and northern regions to well-developed east coast provinces. Capital investment dominated the cross-boundary effect (56% of the total) by involving substantial equipment and construction products, which greatly rely on product exports from regions with specific resources. This supply chain-based analysis provides a comprehensive quantification and may inform more effective joint-control efforts among associated regions and sectors from a health risk perspective.

1. Introduction

China's rapid economic development and urbanization in recent years have been accompanied by substantial energy consumption and severe atmospheric pollution, resulting in more than one million premature deaths annually [1]. In response, since 2013, the Chinese government has launched a series of mitigation actions national widely, including the toughest-ever Air Pollution Prevention and Control Action Plan (the Action Plan, 2013–2017) and the Three-Year Action Plan for Winning the Blue-Sky Defense Battle (the Three-year Plan, 2018–2020). During this time, China's population-weighted fine particle matter ($PM_{2.5}$) concentration steadily decreased from 63 $\mu g\ m^{-3}$ in 2013 to 45 $\mu g\ m^{-3}$ in 2017 and finally to 33 $\mu g\ m^{-3}$ in 2020 [2,3], just below the interim target I (35 $\mu g\ m^{-3}$) suggested by the World Health Organization (WHO) but still much higher than the suggested health standard ($\leq 5\ \mu g\ m^{-3}$) [4]. With the rapid economic expansion and increasing margin abatement costs, further pollution reduction involving traditional end-of-pipe oriented strategies could experience notable difficulties from both technical and economic perspectives [5]. To maintain a further decreasing trend, the Chinese government should devote more effort to promoting the structure readjustment process in energy, industry, and transportation systems to achieve clean air in China [6,7].

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https://doi.org/10.1016/j.ese.2023.100264

Industrial restructuring to obtain a clean pattern relies upon a deep understanding of the interaction among industries and regions, as product trade plays an ever-increasing prominent role in relocating pollution and associated health burdens among sectors and regions [8]. In recent years, with the development of multidisciplinary models, air pollution and associated environment and/or social impacts transfer among regions and sectors have been intensively studied. The study objects range from specific pollutant emissions [8–12] to emission-related $PM_{2.5}$ concentrations [13–17] and further extend to pollution-associated health burdens [18–23]. As atmospheric pollution is a combined effect of complex physical and chemical reactions of various species [primary $PM_{2.5}$ and inorganic $PM_{2.5}$ precursors (mainly including SO_2, NO_x, VOC, NH_3)] under certain geographical and meteorological conditions, thus trade associated pollution and related health burden analysis can represent trade's effect more comprehensively. While existing studies always focused on aggregated results from production, consumption, and/or export perspectives [13–23], they provided less information on sectors and their interaction through trade chains. Sectors are the basic units to implement pollution control measures in practice, and the lack of their health risk evaluation may hinder the joint control actions among regions and sectors. In recent years, some studies tried to track pollution-associated health impacts along the trade chains [12,24]. While these studies only focus on the primary $PM_{2.5}$, which only contributed less than half of the total anthropogenic $PM_{2.5}$ pollution and was dominated by different sectors from other species [25–27], thus cannot represent the whole effect of trade.

Here, we focus on China's interprovincial trade and present a comprehensive analysis of anthropogenic $PM_{2.5}$-related health burden transfer along product chains among regions and sectors by combining five state-of-the-art models from physics, economy, and epidemiology. This supply chain-based analysis could provide a comprehensive quantification and may inform more effective joint-control efforts among associated regions and sectors. Details of the models and model integration are provided in Section 2 and Fig. S1. In summary, we used satellite-based $PM_{2.5}$ concentration data, and concentration–response functions (CRFs) retrieved from the Global Burden of Disease Study 2019 (GBD2019) [28] to estimate $PM_{2.5}$-related premature mortality. We then used a chemical transport model driven by the China air pollution inventory to attribute $PM_{2.5}$ pollution and related health impacts to various emission source regions and sectors. Finally, we traced the sectoral production-based health burden to the consuming regions and sectors along the domestic supply chains by using a multiregional input–output (MRIO) model over Chinese mainland. Pollution-associated premature deaths were finally attributed to various production and consumption sectors along the supply chains. Notably, regional production-based pollution deaths refer to emission-associated pollution deaths that occurred in China nationally, widely due to atmospheric transport.

2. Material and methods

2.1. $PM_{2.5}$-related premature mortality

$PM_{2.5}$-related premature mortality was calculated based on $PM_{2.5}$ mass concentrations and the exposure-response model. To reduce the uncertainty due to chemical transport models, the $PM_{2.5}$ concentration in 2017 derived from Tracking Air pollution in China (TAP: http://tapdata.org.cn/) was used to constrain the spatial distribution of $PM_{2.5}$ within China. TAP is a full-coverage, high-resolution air pollution product that combines information retrieved from multisource data fusion and provides a more reliable $PM_{2.5}$ map of China [2].

The newest CRFs derived from the GBD2019 [28] were chosen here to estimate $PM_{2.5}$-related mortality. The GBD2019 study avoided the use of active smoking data for the first time and included cohort studies in pollution-intensive regions, including China [29,30] and other lower-income countries [31]. In GBD2019, the Meta Regression-Bayesian, Regularized, Trimmed (MR-BRT) splines were used to fit the considered risk data with a more flexible shape, which could reflect the $PM_{2.5}$-associated risk more accurately [28].

The GBD2019 study considered the $PM_{2.5}$-related health risk to the non-accidental mortality resulting from adult (25 years and older) ischemic heart disease (IHD), stroke (ischemic and hemorrhagic), chronic obstructive pulmonary disease (COPD), lung cancer, and type II diabetes (DM2), and childhood and adult (younger than 5 years and 25 years and older) acute lower respiratory infection (LRI). The relative risk (RR) for each endpoint at exposure C_{tap} can be calculated as:

$$\mathrm{RR}(C_{\text{tap}}) = \begin{cases} 1, C_{\text{tap}} \le tmrel \\ \dfrac{MRBRT(C_{\text{tap}})}{MRBRT(tmrel)}, C_{\text{tap}} > tmrel \end{cases} \tag{1}$$

Where C_{tap} is the $PM_{2.5}$ concentration derived from TAP model; $RR_{C_{tap}}$ is the relative risk which is modeled by using the MR-BRT model; *tmrel* is the theoretical minimum risk exposure level and the GBD2019 released 1000 samples with a uniform distribution from 2.4 to 5.9 $\mu g\ m^{-3}$.

The attributable fraction (*AF*) of the premature mortality attributed to $PM_{2.5}$ exposure can be calculated as:

$$AF = \frac{RR - 1}{RR} \tag{2}$$

The mortality rate (*mr*) attributed to $PM_{2.5}$ exposure can be calculated as:

$$mr = B \times AF \tag{3}$$

where *B* is the baseline mortality incidence rate for a given disease endpoint. The age-specific mortality incidence rates by country in 2017 were derived from the GBD2019 [28]. Finally, the premature mortality (*Mort*) attributed to $PM_{2.5}$ exposure can be calculated as:

$$Mort = P \times B \times AF \tag{4}$$

where *P* is the population. Gridded population datasets were obtained from the Global Population for the World (GPW) dataset [32]. All steps were implemented for concerned age groups at 5-year intervals and a grid resolution of 36 km.

2.2. $PM_{2.5}$ -related mortality attributed to emission sources and sectors

The regional $PM_{2.5}$ concentration results from the complex physical and chemical reactions of various pollutants emitted in both local and surrounding regions. Here, we used a reduced-complexity Intervention Model for Air Pollution (InMAP) developed for China [33] to attribute grid-specific $PM_{2.5}$ concentrations to location- and species-specific emissions.

The InMAP was originally developed by Tessum et al. [34]. It estimates annual average pollutant concentrations by approximating the steady-state solution with atmospheric transport equations. The InMAP solves equations by discretizing over space and time with spatially varying parameterizations that simplify the complex reaction, advection, and removal terms in the equations.

With this simplification, the InMAP can predict annual average $PM_{2.5}$ concentrations within a few hours and has been an easy and faster model to inform strategies to reduce $PM_{2.5}$-related mortality from specific emission sources or products [26,35–37].

The InMAP for China used in this study was developed and evaluated in our previous studies [33], which covered eastern Asia at 36 km resolution. The anthropogenic emissions in China were derived from the Multi-resolution Emission Inventory for China (MEIC: http://meicmodel.org), the anthropogenic emissions in East Asia outside China were obtained from the MIX (a mosaic Asian anthropogenic emission inventory) [38], and biogenic emissions retrieved from the Model of Emissions of Gases and Aerosols from Nature (MEGAN) v2.10. Anthropogenic emissions of primary $PM_{2.5}$ and precursor gases, such as sulfur dioxide (SO_2), nitrogen oxides (NO_x), ammonia (NH_3), and nonmethane volatile organic compounds (NMVOCs), were included in the simulation. The InMAP model can explicitly trace their contributions to primary $PM_{2.5}$ or secondary $PM_{2.5}$ (including particulate ammonium (pNH_4), particulate sulfate (pSO_4), particulate nitrate (pNO_3), and secondary organic aerosols (SOA)). A detailed description of the model, parameter configuration, and model evaluation for 2017 can be found in our previous study [33].

For the InMAP model, the estimated $PM_{2.5}$ concentration in a given grid j can be expressed as:

$$C_j = \sum_k \sum_i S_{i,j}^k \times E_i^k \tag{5}$$

where $S_{i,j}^k$ is the partial derivative of the cost function to the anthropogenic emissions in grid i within the domain, which indicates the sensitivity of the $PM_{2.5}$ concentration in grid j to the emissions of species k in grid i (E_i^k).

To minimize the uncertainty of the InMAP, we normalized the contribution of the grid- and sector-specific emissions by using the $PM_{2.5}$ concentration in targeted grid j (C_j) as:

$$P_{i,j}^s = \frac{\sum_k S_{i,j}^k \times E_i^{k,s}}{C_j} \times 100\% \tag{6}$$

$$P_{i,j} = \sum_s P_{i,j}^s \tag{7}$$

where $E_i^{k,s}$ is species k emissions from sector s in grid i, and $P_{i,j}^s$ define the contribution of the total emissions from sector s in grid i to the $PM_{2.5}$ concentration in grid j.

Following our previous studies, we applied the direct proportion approach to estimate the contribution of the grid- and sector-specific emissions to the $PM_{2.5}$-related mortality in grid j as:

$$Mort_{i,j}^s = P_{i,j}^s \times Mort_j \tag{8}$$

The national $PM_{2.5}$-related mortality ($Mort_n$) attributed to emissions in a given region r, and its sector s can be calculated as:

$$Mort_{r,n} = \sum_{i \in r} \sum_s \sum_{j \in n} Mort_{i,j}^s \tag{9}$$

$$Mort_{r,n}^s = \sum_{i \in r} \sum_{j \in n} P_{i,j}^s \times Mort_j \tag{10}$$

To get sector-specific mortality in MRIO sectors used in the following section, we use the emission mapping process between MEIC sectors to MRIO sectors described in our previous study [9,10], to attribute $PM_{2.5}$-related mortality to MRIO sectors (s'):

$$P_{i,j}^{s'} = \frac{\sum_k S_{i,j}^k \times (E_i^{k,s} \times r_i^{k,s \to s'})}{C_j} \times 100\% \tag{11}$$

$$Mort_{r,n}^s = \sum_{i \in r} \sum_{j \in n} P_{i,j}^{s'} \times Mort_j \tag{12}$$

here $r_i^{k,s \to s'}$ refer to the sectoral emission conversion factor between MEIC sectors and MRIO sectors. The mapping relation between the MEIC sectors and socioeconomic sectors can be found in Fig. S2.

2.3. $PM_{2.5}$-related mortality embodied in product supply chains

MRIO model could be employed to represent the complex material exchange among sectors and regions, thus enabling us to capture the cumulative production and associated impact along the supply chains triggered by the finished products or consumption activity [8]. Here we used the latest non-competitive 31-province, 42-sector MRIO table in 2017 for China compiled by Zheng et al. [39] to attribute the sectoral production-based pollutant emissions and associated $PM_{2.5}$-related mortality to various communities (sector, region, or final demand) along the domestic supply chains within China.

The balance of monetary MRIO analysis can be written as follows:

$$\begin{pmatrix} \mathbf{x}^1 \\ \mathbf{x}^2 \\ \mathbf{x}^3 \\ \vdots \\ \mathbf{x}^m \end{pmatrix} = \begin{pmatrix} \mathbf{A}^{1,1} & \mathbf{A}^{1,2} & \mathbf{A}^{1,3} & \cdots & \mathbf{A}^{1,m} \\ \mathbf{A}^{2,1} & \mathbf{A}^{22} & \mathbf{A}^{2,3} & \cdots & \mathbf{A}^{2,m} \\ \mathbf{A}^{3,1} & \mathbf{A}^{3,2} & \mathbf{A}^{3,3} & \cdots & \mathbf{A}^{3,m} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \mathbf{A}^{m,1} & \mathbf{A}^{m,2} & \mathbf{A}^{m,3} & \cdots & \mathbf{A}^{m,m} \end{pmatrix} \begin{pmatrix} \mathbf{x}^1 \\ \mathbf{x}^2 \\ \mathbf{x}^3 \\ \vdots \\ \mathbf{x}^m \end{pmatrix} + \begin{pmatrix} \sum_s \mathbf{y}^{1,s} \\ \sum_s \mathbf{y}^{2,s} \\ \sum_s \mathbf{y}^{3,s} \\ \vdots \\ \sum_s \mathbf{y}^{m,s} \end{pmatrix} \tag{13}$$

where $\mathbf{x}^r$ is a vector of the total economic output of region r by sector, $\mathbf{y}^{r,c}$ is the final demand vector by sector produced in region r and consumed in region c, and $\mathbf{A}^{r,c}$ is a normalized matrix of intermediate coefficients, representing the input stemming from sectors in region r required to produce one unit of output from each sector in region c.

Under this framework, the emission-associated premature deaths embodied in the sector-specific consumption of region c by source can be obtained as:

$$Mort^{\cdot c} = \widehat{\boldsymbol{f}} (\mathbf{I} - \mathbf{A})^{-1} \mathbf{y}^{\cdot c} \tag{14}$$

where $Mort^{\cdot c}$ is a vector of the region- and sector-specific $PM_{2.5}$-related deaths flowing toward consuming region c, $\widehat{\boldsymbol{f}}$ is the diagonalization of the vector of the region- and sector-specific $PM_{2.5}$-related deaths for the unit output, which is derived from the sector-specific $PM_{2.5}$-related deaths determined with equation (12) and the total output vector of the MRIO model, and $\mathbf{y}^{\cdot c}$ is the final demand vector of region c.

2.4. Uncertainty analysis

Our study is subject to a number of uncertainties due to the inherent assumptions and limitations of the adopted models, including emission inventories, chemical transport model, satellite-based $PM_{2.5}$ concentration, MRIO model, and the health impact models. To reduce the uncertainties, we have chosen the latest and state-of-the-art models in each step, and a detailed discussion of the advance, limitations, and/or uncertainty of each model is presented in the *Supplementary Information.* As discussed in the *Supplementary Information*, a comprehensive uncertainty analysis combining all influencing factors is impossible due to the limitation of the computational load, especially for the sensitivity simulation of gridded $PM_{2.5}$ concentration to national wide pollutant emissions. The $PM_{2.5}$-related mortality presented in the main text was calculated based on the mean value of the parameters in each model.

3. Results

3.1. $PM_{2.5}$-related mortality along domestic supply chains

$PM_{2.5}$ concentration in China was estimated at 45 μg m^{-3} in 2017 and resulted in 1.36 million premature deaths. Source apportionment results indicated that 96% of the deaths (1.32 million) could be attributed to anthropogenic emissions from China. Unless otherwise specified, $PM_{2.5}$-related premature deaths hereinafter refer to deaths attributed to anthropogenic sources within China.

Fig. 1a and Tables S2–4 summarize the anthropogenic $PM_{2.5}$-related deaths along China's domestic supply chains by linking the $PM_{2.5}$-related deaths transferring among specific communities, including combusted energy type/emission processes (1st column of Fig. 1a), sectors producing emissions (2nd column), sectors manufacturing the final goods or services (3rd column), and final demands consuming the goods or services (4th column). To facilitate the presentation, the sector classifications were aggregated into 14 representative sectors (Table S1), and their contribution to $PM_{2.5}$-related mortality was converted into the ratios of relative death numbers to the national total.

Sector-specific $PM_{2.5}$-related deaths exhibited great diversity in production/emission sources, reflecting their different emphasis for future mitigation actions (1st and 2nd columns of Fig. 1a). Industrial sectors dominated the $PM_{2.5}$-related deaths in China, as they are highly dependent on coal combustion and heavily polluted industrial processes. The nonmetal, metal, and energy sectors ranked in the top three among industrial sectors and contributed to 12.1%, 11.5%, and 13.4% of China's total, respectively. While the nonmetal and energy sectors were dominated by coal combustion, and the metal sector was dominated by industrial processes, primarily involving the sintering process of iron and steel [27]. The less controlled agricultural and rural residential sectors also contributed remarkably (14% and 17.6%, respectively). The high ratio for the agricultural sector could be attributed to its substantial NH_3 emissions from fertilizer use and animal husbandry (accounting for ~90% of China's anthropogenic NH_3 emissions [27]), which play a dominant role in the formation of ammonium sulfate and nitrate [40]. The high ratio for rural residential direct energy use was derived from its disproportionately high emissions of primary $PM_{2.5}$, resulting from the inefficient combustion of biofuel and raw coal in traditional stoves [41]. Transportation contributed 11.2% to the total $PM_{2.5}$-related deaths in China; more than 98% of these can be attributed to oil consumption.

By summarizing all deaths attributed to emissions along upstream supply chains, the 3rd column of Fig. 1a highlights the underlying drivers of $PM_{2.5}$-related deaths in China from a

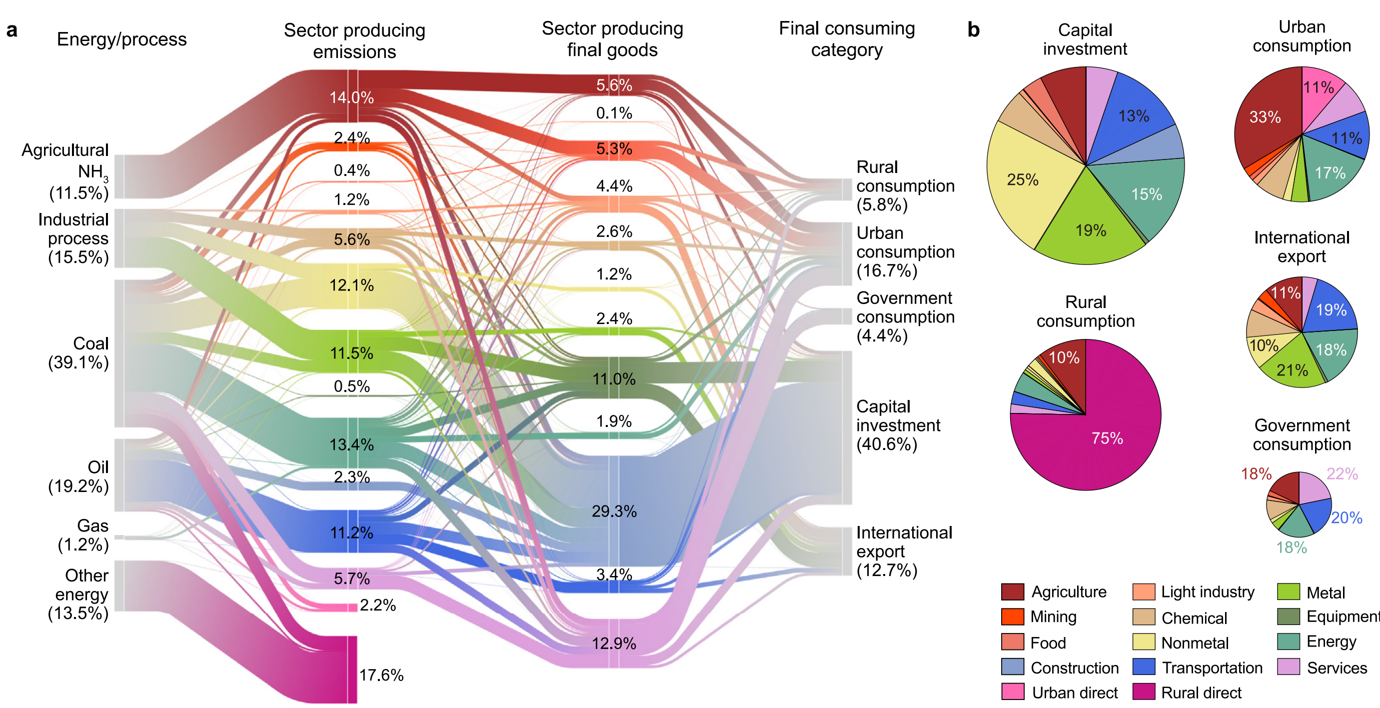

Fig. 1. a, Flow map highlighting the industrial sectors involved in the $PM_{2.5}$-related deaths embodied in the China supply chains. The energy/process specifies combusted energy types and processes generating related emissions, and these processes are then mapped to the specific industrial sectors encompassing the process. These production sectors are then mapped to the sectors producing the final goods or services and further to the final demand categories those consuming the final goods or services. The width of the lines and labeled percentages indicate the relative contributions to the anthropogenic $PM_{2.5}$-related premature deaths in China in 2017 (1.32 million). **b**, The ranking of the final demand categories and their source composition based on emission production sectors. The rural and urban consumption-related values also include those attributed to rural and urban direct energy consumption.

consumption perspective. The services, equipment, food, and light industry sectors were highlighted and accounted for 29.3%, 12.9%, 11.0%, 5.3%, and 4.4%, respectively, of China's total, which was at 13, 2, 22, 14, and 4 times their respective ratios from a production perspective (2nd column). Among these, 51% and 42% of the respective premature deaths driven by the construction and equipment sectors originated from the emissions of the metal and nonmetal sectors, and 67% of the deaths driven by the food sector derived from agricultural production.

The 4th column of Fig. 1a finally attributes the embodied $PM_{2.5}$-related deaths to the final demands (e.g., rural consumption, urban consumption, government consumption, capital investment, and international export). Capital investment was the largest contributor, as it involved 51% and 99% of the respective total effects of the final construction and equipment products, which drove substantial production and associated effects in heavily polluted upstream sectors (2nd column). As estimated, 60% of the mortality driven by capital investment can be attributed to emissions from nonmetal, metal, and energy sectors (Fig. 1b). Rural and urban consumption contributed similar shares (23.4% and 19%, respectively). While rural consumption was dominated by direct emission activities and urban consumption was dominated by indirect emissions stemming from the consumption of products/services from the agriculture, food, and service sectors. This, to some extent, indicates their difference in mitigation strategies in the future [42]. International exports attained a similar ratio (12.7%) to previous years [15,19], primarily through the export of equipment, light industry, and chemical products. Government consumption ranked the last (4.4%), and 85% of its impact resulted from the consumption of various services, which drove a certain number of $PM_{2.5}$-related deaths sourced from the agricultural, energy, and transportation sectors.

3.2. Relocation of demand-driven $PM_{2.5}$-related mortality among regions

Product trade among regions resulted in pollution responsibility and associated health impact relocation from consuming regions to producing regions. As estimated, in 2017, 339,000 $PM_{2.5}$-related deaths in China could be attributed to interprovincial trade, which accounted for 25.7% of the national total. Fig. 2 shows the net effect of $PM_{2.5}$-related death transfer among regions and those driven by specific final demand categories (Fig. 2a–c), and Fig. S3 shows their geographic distribution. The effects of rural, urban, and government consumption were aggregated, allowing for their similar service subjects.

Geographically, the dominant feature was the export of embodied $PM_{2.5}$-related deaths from central and northern China to eastern, southeastern, and southwestern China (Fig. 2d and Fig. S3d), but with varying magnitudes and patterns shaped by different final demand categories (Fig. 2a–c and Figs. S3a–c). Even though the consumption-associated effect was greater than that driven by capital investment and far greater than that driven by international exports (Fig. 1), its cross-boundary effect was less obvious (Fig. 2a and Fig. S3a) than those driven by the other factors partially reflecting that consumption activities tended to rely more on local production. Accordingly, less prominent net fluxes were observed from Henan and Hebei to well-developed and populous Beijing, Jiangsu, Zhejiang, and Guangdong (Fig. S3a).

Capital investment dominated the $PM_{2.5}$-related deaths transfer among regions (56% of the national total; Fig. S4b), as well as the net flow pattern (Fig. 2b). Net export regions were mainly concentrated in heavy industrial provinces (e.g., Henan, Hebei, and Anhui) or energy-oriented provinces (Nei Mongol and Shanxi) (Fig. 2b). The $PM_{2.5}$-related deaths embodied in interprovince

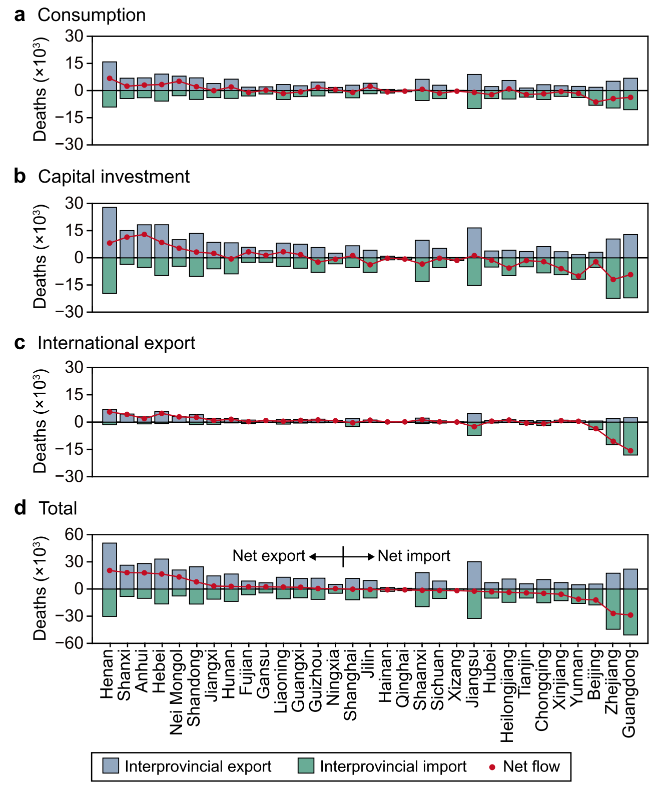

Fig. 2. $PM_{2.5}$-related premature mortality embodied in interprovincial trade driven by specific final demand categories (**a**–**c**) and their aggregated effects (**d**). In panel **a**, consumption includes the aggregated effect of rural, urban, and government consumption.

export from these regions accounted for 36% of the corresponding national total amount (89,396 premature deaths), two times that embodied in their interprovince imports (43,162 premature deaths; 18% of the national total). However, the net import regions driven by capital investment were more dispersed in space. In addition to the abovementioned well-developed eastern and southeastern coastal provinces, certain western and northeastern provinces, such as Chongqing, Yunnan, Shaanxi, Xinjiang, Heilongjiang, and Jilin, also were notable net importers due to their substantial imports from central and northern regions to support local infrastructure construction, but with relatively low $PM_{2.5}$-related death outflows (Fig. S4b). This, to a certain extent, reflects China's effort to reindustrialize the western and northwest regions over the past few years.

The $PM_{2.5}$-related deaths transfer driven by international exports was more concentrated in terms of geography (Fig. 2c and Fig. S3c). International exports solely from Guangdong and Zhejiang contributed 40% to China's total effects driven by international exports, but almost half of this ratio (46%) could be attributed to the upstream sectors in other regions (Fig. S4c). Accordingly, most of the highest net fluxes occurred from other regions toward Guangdong and Zhejiang. The $PM_{2.5}$-related deaths embodied in the international exports of Jiangsu and Shandong were also significant (23% of the national total). But as these exports relied more on local supply chains, only 23% of the corresponding death number occurred in other regions (Fig. S4c).

3.3. $PM_{2.5}$-related mortality transfer among regions by sectors

The transfer of $PM_{2.5}$-related deaths among regions was usually dominated by the products of specific sectors. From a production perspective, in 2017, 66% of the $PM_{2.5}$-related deaths transferred among regions in China could be traced back to the agricultural, nonmetal, metal, and energy sectors—the leading contributors shown in Fig. 1a. Fig. 3 highlights the hotspots of $PM_{2.5}$-related deaths transfer among regions originated from these four sectors, separately, and reveals notable diversity among regions and sectors. Regarding the agriculture sector, the leading export regions were primarily concentrated in China's agrarian regions, including Henan, Hunan, Anhui, Jiangsu, and Hebei (Fig. 3a). Jointly, these regions accounted for 46% of the total $PM_{2.5}$-related deaths driven by agricultural product trade, and Henan solely contributed 14%. According to the statistics, these five provinces accounted for 27% of the agricultural gross domestic product of China in 2020 [43]. Regions adjacent to more affluent east coastal/or populous regions also bore significant $PM_{2.5}$-related deaths resulting from the export of agricultural products to their neighbors, directly and indirectly, such as from Guizhou (1,048 deaths) and Guangxi (1,133 deaths) to Guangdong, from Nei Mongol to Hebei (892 deaths) and Shanxi (944 deaths), and from Shaanxi (1,313 deaths) to Henan.

The cross-regional $PM_{2.5}$-related deaths transfer caused by the nonmetal sector were more scattered in spatial and highlighted prodigious effects between specific regions (Fig. 3b). For example, the pollution-associated deaths embodied in nonmetal exports only from Anhui and Henan accounted for 32% of the national total (20,059 deaths). The sole effect between Anhui and Jiangsu

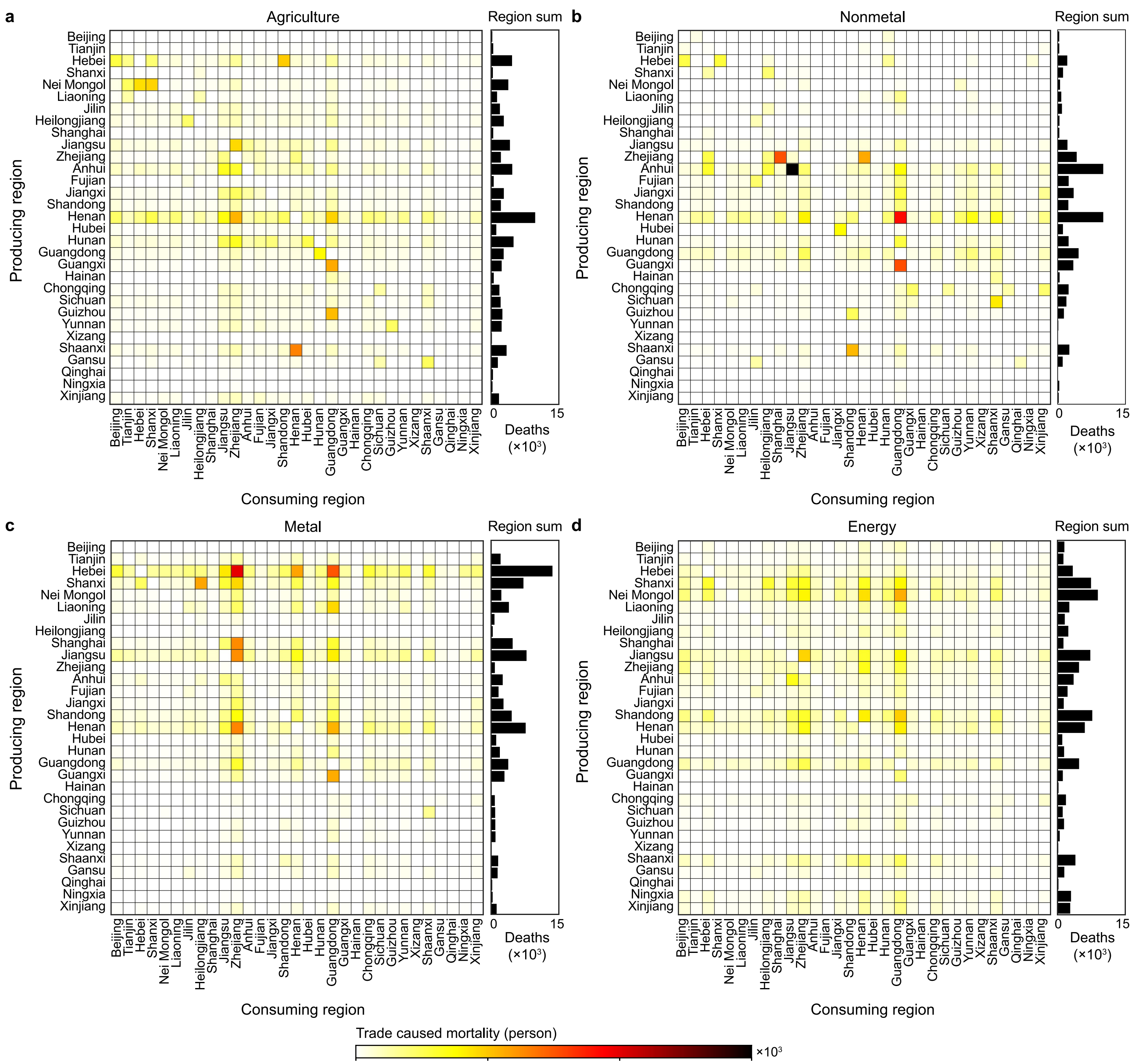

Fig. 3. Sector-specific $PM_{2.5}$-related deaths transfer driven by interprovincial trade. Grids located in the diagonal line from the upper left to the lower right in each panel represented regional impacts on themselves and were set as zeros. The bar figure on the right of each panel shows the sum effect of trade on each region.

amounted to 4,578 premature deaths. As estimated, Anhui solely produced 6% of China's cement production in 2020 [44]. The effect originating in Henan (2,056 deaths) and Guangxi (1644 deaths) and exported to Guangdong were also significant. Compared to nonmetal products, $PM_{2.5}$-related death transfer driven by metal products was more geographically concentrated from both export and consumption perspectives (Fig. 3c). Exporting regions were primarily concentrated in Hebei, Shanxi, Jiangsu, and Henan, while consuming regions were mainly concentrated in Zhejiang and Guangdong, partly attributed to their substantial international export of equipment products. Regarding Hebei, its metal production caused 22,524 premature deaths in China, accounting for 15% of the total national effects from metal production; and 60% of this effect (13,439 deaths) can be attributed to meeting the final demand in other domestic regions.

Compared to other sectors, $PM_{2.5}$-related death transfer driven by the energy sector was more evenly distributed among regions (Fig. 3d), which could be attributed to its power properties—serving as energy to facilitate production and export in other sectors. As expected, the largest exporter occurred in Nei Mongol—China's main energy base—produced 9% of China's thermal power generation in 2020 [44].

Fig. 4 ranks the top 50 interprovincial supply chains out of 129,600 items based on their contribution to the number of $PM_{2.5}$-related deaths. These supply chains start from producing regions and sectors and end in consuming regions and sectors, jointly accounting for 8.2% of the national total $PM_{2.5}$-related deaths transferred among provinces. These top supply chains were characterized by large trade regions and all the above-mentioned heavily polluted sectors, such as the metal, nonmetal, agricultural, and energy sectors, as well as heavily polluted sectors from a consumption perspective, such as the construction, agricultural, equipment, and food sectors. To a certain extent, this ranking list reveals the potential targets for joint control actions among specific regions and sectors.

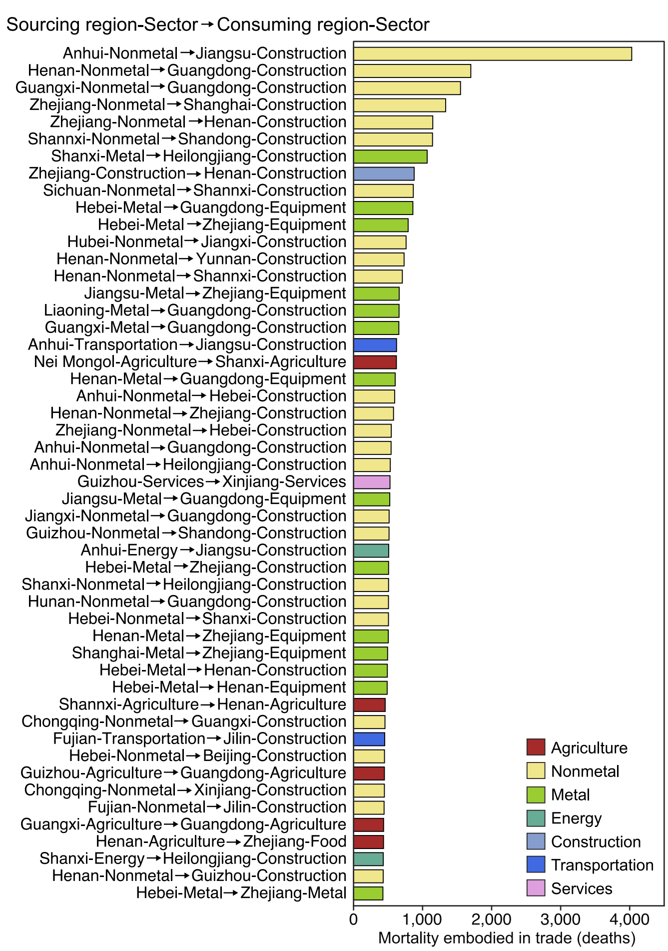

Fig. 4. Ranking of the top 50 supply chains (from emission source regions and sectors to final demand regions and sectors) those driving the $PM_{2.5}$-related mortality the most.

4. Discussions and policy implications

Product trade significantly affects production and associated pollution burden relocation among regions. This study combined five state-of-the-art models and provided a comprehensive picture of how atmospheric $PM_{2.5}$-related premature mortality were driven by consuming regions and sectors through supply chains within China. Our results highlight the key sectors affecting regional air pollution from both production and consumption perspectives and the key final consumption categories (capital investment) and sectors (agricultural, nonmetal, metal, and energy sectors) that dominated the relocation of $PM_{2.5}$-related deaths among provinces. This supply chain-based analysis provides a comprehensive quantification and may inform more effective joint-control efforts among associated regions and sectors.

From an emission production perspective, the less controlled sectors, including the agricultural and rural residential direct energy consumption sectors, contributed equivalent $PM_{2.5}$-related deaths to the targeted sectors, such as the chemical, metal and nonmetal, energy, and transportation sectors (31.6% versus 53.8% of the national total; Fig. 3). If the toxic differences among particulate matter (PM) components [45–47] or indoor air pollution due to solid fuel use [48] were considered, the contribution ratios stemming from the residential sector could be doubled. After the Action plan, the Chinese government reinforced residential pollution control action in Beijing–Tianjin–Hebei and surrounding regions [49], but with less attention on the populous central and southwestern regions of China, where biomass remains a dominant residential energy source and significantly contributes to pollution-associated deaths [41]. To obtain more health benefits, the Chinese government should extend these actions nationwide. In scientific research, NH_3 control in agriculture has been frequently examined, but there is still no concrete action due to a lack of reliable emission inventory and monitoring technologies [50]. With the ever-increasing marginal mitigation costs of primary $PM_{2.5}$, SO_2, and NO_x, promoting relative technology development to incorporate NH_3 in control measures could become more urgent and cost-effective [5,51]. In addition, NH_3 reduction could also alleviate ecosystem acidification and water body eutrophication [52,53]—another important environmental problem currently faced in China [53].

Allowing for the cumulative effects originating from the supply chains, the food, light industry, construction, equipment, and services sectors stood out. It contributed 2–22 times, respectively, to their effects from a production perspective (Fig. 1). Construction and equipment primarily driven by infrastructure-oriented capital investment, dominated the $PM_{2.5}$-related deaths transfers among regions and sectors. In addition, these sectors could further substantially raise committed emissions in their future operating process [54,55]. Hence, current or future infrastructure investments should focus more on their unintended indirect environmental effects. In addition to incorporating sophisticated pollution control action along the production chains and early plans for environmentally friendly eco-design in the operating process, promoting sustainable development of various high-quality industries to coordinate multiple environmental objectives could become increasingly necessary. In regard to residential consumption, by consuming various goods (e.g., food and light industry) and services, urban households contributed similar pollution-associated health burden to that of rural households (19% versus 23.4% of the national total account), partly offsetting the pollution reduction effect of clean energy transition in the urbanization process [56]. Thus, a stimulus green consumption pattern could be urgently required and promoted in the rapid urbanization process to maintain the pollution mitigation effect and clean China's air from a demand-side perspective.

With economic globalization, pollution mitigation action should not be limited to where emissions occur due to pollution “leakage” through product trade [11]. This study greatly quantified $PM_{2.5}$-related deaths embodied in product trade among regions and sectors within China. The results indicated that the agricultural, nonmetal, metal, and energy sectors accounted for 66% of the $PM_{2.5}$-related deaths transfer among regions (Fig. 3). A series of joint control actions focusing on these key sectors among relative regions could help to reduce pollution and associated health burden leakage among regions, such as technology transfer, technology cooperation, or even economic compensation. Pilot projects focus on these cooperative emission reduction actions can be started in Beijing—Tianjin—Hebei, Yangtze River Delta, and their surrounding regions, where trade flows and associated pollution outsourcing is frequent and/or intensive (Figs. 3 and 4). Future research should focus more on cost-effective analysis of technology transfer and/or cooperation among regions and sectors to better formulate and coordinate mitigation efforts.

CRediT author contribution statement

Hongyan Zhao: Conceptualization, Data curation, Visualization, Writing- Original draft preparation. **Ruili Wu**: Software, Validation. **Yang Liu**: Data curation, Validation. **Jing Cheng**: Data curation, Validation. **Guannan Geng:** Conceptualization, Supervision. **Yixuan Zheng**: Writing- Reviewing and Editing. **Hezhong Tian**: Writing-Reviewing and Editing. **Kebin He:** Writing- Reviewing and Editing. **Qiang Zhang:** Conceptualization, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work is supported by the National Natural Science Foundation of China (71904097, 41921005, 91744310 and 42205183), and the Fundamental Research Funds for the Central Universities (2021NTST21).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ese.2023.100264.

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