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Quantifying regional consumption-based health impacts attributable to ambient air pollution in China

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ABSTRACT

Serious air pollution has caused about one million premature deaths per year in China recently. Besides cross-border atmospheric transport of air pollution, trade also relocates pollution and related health impacts across China as a result of the spatial separation between consumption and production. This study proposes an approach for calculating the health impacts of emissions due to a region's consumption based on a multidisciplinary methodology coupling economic, atmospheric, and epidemiological models. These analyses were performed for China's Beijing and Hebei provinces. It was found that these provinces' consumption-based premature deaths attributable to ambient $PM_{2.5}$ were respectively 22,500 and 49,700, which were 23% higher and 37% lower than the numbers solely within their boundaries in 2007. The difference between the effects of trade and trade-related emissions on premature deaths attributable to air pollution in a region has also been clarified. The results illustrate the large and broad impact of domestic trade on regional air quality and the need for comprehensive consideration of supply chains in designing policy to mitigate the negative health impacts of air pollution across China.

1. Introduction

Ambient $PM_{2.5}$ has been estimated to be responsible for 1.2 million premature deaths in China in 2010, or nearly 35% of such deaths worldwide (Lim et al., 2012; Xie et al., 2016; Yang et al., 2013). Beside local sources of air pollution, the air quality of a province might be affected by atmospheric transport of pollution from other distant provinces (Li et al., 2015; Xue et al., 2014) and even from other countries (Anenberg et al., 2014; Lin et al., 2014; Liu et al., 2009; Verstraeten et al., 2015). In addition to physical atmospheric transport, trade also relocates air pollution and its related health impacts because goods are produced in one region and consumed in other regions (Zhang et al., 2017). China is a vast country with substantial disparities across provinces in terms of resource and energy endowment, economic development, and population density, encouraging trade between provinces with consequent embodied pollution (Jiang et al., 2015; Wang et al., 2017; Zhao et al., 2017). In recent years, emissions have grown rapidly in some inland provinces but stabilized or even decreased in many coastal regions (Liu et al., 2013), partly because inland provinces export emission-intensive products (e.g., raw materials or energy) to support production and consumption of finished goods in coastal regions (Feng et al., 2013; Wang et al., 2015; Zhao et al., 2015).

In this paper, we focus on two areas: Hebei province, which surrounds the capital Beijing, and Beijing itself, both locate in the region of China that suffers the most serious air pollution and consequent health impact, i.e., Beijing-Tianjin-Hebei. Beijing's rampant air pollution, especially in the winter, has already been reported frequently in recent years (Yuan et al., 2012; Zeng et al., 2017). As the national capital, Beijing is usually seen as a mirror reflecting severe air pollution in China and it has become a domestic and even global focus of attention.

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This makes Beijing the most important city in China's national air pollution control strategy. Hebei is one of the top five provinces in China in terms of total premature deaths attributable to air pollution, death risk (i.e., per capita premature death) and health burden (i.e., premature death per unit of local GDP) (Xie et al., 2016). In addition, Hebei and Beijing are neighbors with close relationships in supply chains (e.g., Hebei exports goods and materials to Beijing and accepts pollution-intensive industries relocated from Beijing) and greatly influence each other's air quality by means of atmospheric cross-border transport (Wang et al., 2017; Zhao et al., 2017).

Most recently, a few studies (Zhang et al., 2017; Zhao et al., 2017) have discussed the concept of consumption-based health impacts, which is related to, but should not be confused with the evaluation of trade effects on public health due to air pollution. Our previous study (Wang et al., 2017) estimated the effects of both international and domestic interprovincial trade on premature death by linking a global integrated multi-regional input-output model, an air pollutant emissions inventory, an atmospheric chemical transport model, and an exposure-response model. Building on this framework, this study used Beijing and Hebei as examples to investigate further the relationships of production and consumption to premature deaths due to air pollution, i.e., production- and consumption-based health impacts, and discussed their differences with respect to the effects of trade on public health. Although epidemiological associations between elevated ozone concentrations and premature mortality have been found to be independent of associations with $PM_{2.5}$ (Bell et al., 2004; Jerrett et al., 2009), premature deaths from O_3 exposure are far fewer, around 5% globally compared to deaths from $PM_{2.5}$ in 2010 (Lelieveld et al., 2015; Lim et al., 2012). Therefore, only premature deaths attributable to ambient $PM_{2.5}$ were estimated to indicate the air pollution related health impacts in this study.

2. Methods

We have developed an integrated model considering trade between 30 Chinese provinces (excluding Tibet, Hong Kong, Macao, and Taiwan) and 40 other countries and regions and quantified the effects of both interprovincial and international trade on premature deaths attributable to ambient $PM_{2.5}$ across China in 2007 (Wang et al., 2017). Based on this framework, an approach for calculating regional consumption-based health impact attributable to ambient air pollution has been proposed.

The analytical approach proposed here includes three major components (Fig. 1). First, emissions embodied in trade between Chinese provinces and other countries and regions are calculated using a global linked multiregional input-output (MRIO) model. Second, the nested grid GEOS-Chem model is used to estimate the spatial change ratios of ambient $PM_{2.5}$ concentrations induced by emissions related to regional production and consumption. Third, an integrated exposure-response model (IER) is used to examine premature deaths attributable to ambient $PM_{2.5}$ caused by emissions related to regional production and consumption.

2.1. Calculation of consumption-based emissions

The Multi-Resolution Emission Inventory for China (MEIC) (He, 2012) and the Emissions Database for Global Atmospheric Research (EDGAR) (http://edgar.jrc.ec.europa.eu/) were used to estimate production-based emissions for Chinese provinces and for other countries and regions respectively. The linked MRIO model integrating China's MRIO model with the World Input-Output Database (WIOD) developed in our previous study (Wang et al., 2017) was then used to capture the complex economic interconnections among sectors and regions and to assign the emissions generated throughout the supply chains to the region where the finished goods were ultimately consumed. Therefore, the emissions generated in one region (i.e., production-based emissions) could be quantitatively decomposed into the components related to consumption activities in its own and other regions (Eq. (1)). Moreover, emissions related to regional consumption (i.e., consumption-based emissions) could be calculated by subtracting exported and adding imported emissions from regional total production-based emissions (Eq. (2)):

$$E_r^P = \sum_{s=1}^{30} (f_{r,s} \times E_r^P) \tag{1}$$

$$E_r^C = E_r^P - \sum_{\substack{s=1\\ s\neq r}}^{30} (f_{r,s} \times E_r^P) + \sum_{\substack{s=1\\ s\neq r}}^{30} (f_{s,r} \times E_s^P) \tag{2}$$

where E^P and E^C represent the emissions related to regional production and consumption, respectively; r and s represent the 30 provinces in China; $f_{r,s}$ ($f_{s,r}$) represent the fraction of production in region r (s) related to consumption in another region s (r), which could be derived from the linked MRIO model.

2.2. Evaluation of premature deaths attributable to ambient $PM_{2.5}$

Premature deaths from ischemic heart disease (IHD), cerebrovascular disease (stroke), chronic obstructive pulmonary disease (COPD), and lung cancer (LC) attributable to ambient $PM_{2.5}$ were quantified according to the Global Burden of Diseases (GBD) project (Apte et al., 2015; Lim et al., 2012) by means of Eqs. (3)–(5). Premature deaths were calculated for each grid cell at a resolution of 10 km × 10 km and were aggregated for each province.

$$M = AF \times B \times Pop \tag{3}$$

$$AF = \frac{\sum p_i (RR(C)_i - 1)}{\sum p_i RR(C)_i} \tag{4}$$

$$M_i = \frac{RR(C)_i - 1}{\sum p_i RR(C)_i} \times B \times Pop \times p_i \tag{5}$$

where M and M_i are respectively the premature deaths attributable to ambient $PM_{2.5}$ of a given disease in a region and in a grid cell i; AF is the attributable fraction; B is the incidence of the given health effect due to a specific disease (e.g., deaths due to IHD per 1000 people), reported at the national level due to data limitations in China (NBSC, 2008); Pop is the regional exposed population; p_i is the proportion of the population in grid cell i, %; and $RR(C)_i$ is the relative risk of grid cell i at a given $PM_{2.5}$ concentration C.

Following (Burnett et al., 2014), the integrated exposure-response (IER) model was used to calculate $RR(C)$ for each grid cell. The model can be expressed as Eq. (6):

$$RR(C) = \begin{cases} 1 & \text{for } C \le C_0 \\ 1 + \alpha\{1 - \exp(-\gamma(C - C_0)^{\delta})\} & \text{for } C > C_0 \end{cases} \tag{6}$$

where $RR(C)$ is the relative risk of a given $PM_{2.5}$ concentration C; C_0 is the threshold $PM_{2.5}$ concentration below which there is no additional risk; and α, γ, and δ are parameters describing the overall shape of the exposure-response curve resulting from a stochastic fitting process. For each endpoint, the RR function was implemented as in Eq. (6) using the parameters C_0, α, γ, and δ, which were derived based on Monte Carlo simulation, leading to 1000 sets of exposure-response functions (Burnett et al., 2014). The upper and lower bounds (i.e., 2.5 percentile and 97.5 percentile of the 1000 RR estimates) in these plots were used to represent the 95% confidence intervals (CI95) for the estimated premature deaths.

2.3. Attribution of premature death to regional consumption and production

The GEOS-Chem model (v10-01, http://geos-chem.org/) was used to simulate the spatial change ratios of $PM_{2.5}$ concentrations across China attributable to the emissions of individual regional activities (e.g., international export, interprovincial trade, local production and

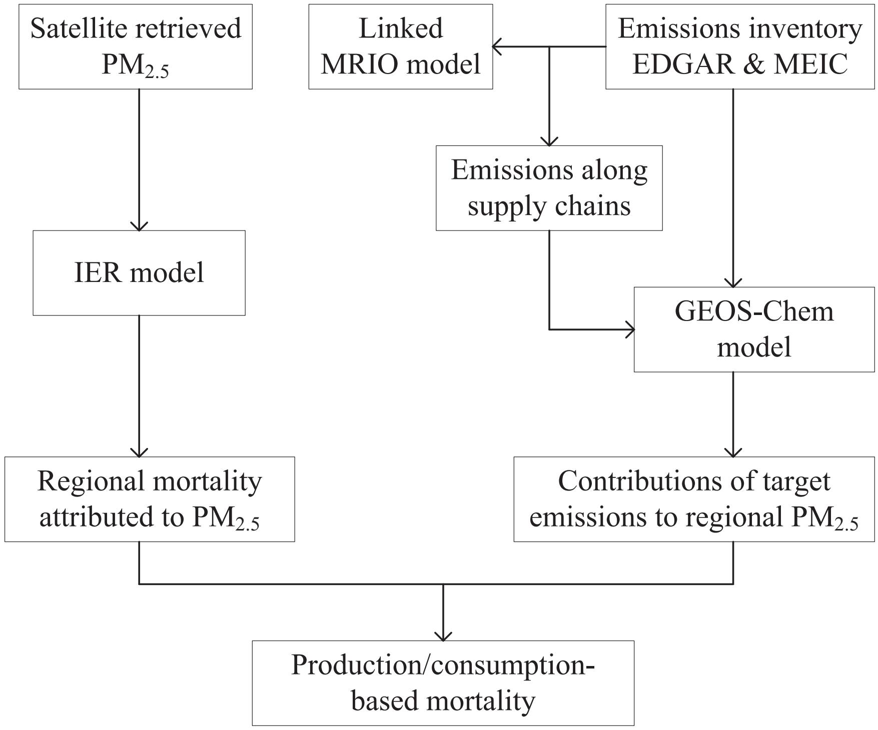

Fig. 1. Methodology framework to evaluate the health impact of emissions related to consumption and production of a region.

consumption) at a resolution of 0.5° latitude × 0.667° longitude (a nominal resolution of ~50 km). The MEIC and EDGAR inventories were used to simulate China's baseline $PM_{2.5}$ concentrations in 2007. Another three simulations were conducted by alternatively removing the emissions related to a region's production, export, and import activities, i.e., a zero-out approach. The spatial change ratios between baseline $PM_{2.5}$ concentrations and the alternative simulated results are considered as the contributions to $PM_{2.5}$ concentrations of emissions related to various activities.

Given the nonlinear relationship of the IER functions, the direct proportional approach, which assumes that the pollution health impact of one source is directly proportional to its contribution to the ambient $PM_{2.5}$ concentration, was used to estimate premature deaths attributed to the emissions related to a region's production and consumption. The scientific basis of this assumption has already been mathematically proved (GBD MAPS Working Group, 2016). This proportional approach has also been applied to estimate the pollution health impacts related to household cooking (Chafe et al., 2014), coal consumption (GBD MAPS Working Group, 2016), road transportation (Anenberg et al., 2017), and international trade (Zhang et al., 2017).

For a given region, premature deaths due to emissions related to its various activities (e.g., production, exports, imports) can be calculated by multiplying the contributions of each to baseline ambient $PM_{2.5}$ concentrations by the total $PM_{2.5}$-related mortalities for each grid cell (Eqs. (8) and (9)).

$$M_r^{P,E,I} = \sum_i M_i \times F_{r,i}^{P,E,I} = \sum_i M_i \times \frac{C_{i,base} - C_{i,r}^{P,E,I}}{C_{i,base}} \quad (8)$$

$$M_r^C = M_r^P - M_r^E + M_r^I \quad (9)$$

where $M_r^{P,E,I}$ are respectively the health impacts of emissions related to production, exports or imports for a region r; M_r^C is the health impact of emissions related to consumption in region r (i.e., consumption-based health impact); $F_{r,i}^{P,E,I}$ are the GEOS-Chem modeled contributions to $PM_{2.5}$ concentration in grid cell i due respectively to emissions related to production, exports and imports of region r; $C_{i,base}$ is the GEOS-Chem modeled $PM_{2.5}$ concentration of grid cell i in the baseline scenario; and $C_{i,r}^{P,E,I}$ are the GEOS-Chem modeled concentrations in alternative scenarios where the emissions related to production, exports or imports in region r have been removed.

3. Results and discussion

3.1. Premature deaths attributable to ambient $PM_{2.5}$ in China

The calculations reported here suggest that premature deaths in 2007 from stroke, COPD, LC, and IHD attributable to ambient $PM_{2.5}$ were 606,400 (CI95: 411,400–762,400), 184,400 (164,800–207,000), 124,500 (103400–142,700), and 191,300 (171,600–239,100), which accounted for 40%, 20%, 25% and 27% respectively of China's total deaths for these four health endpoints. The estimate of 1.10 million premature deaths in 2007, which represented nearly one-third of the global total mortality due to ambient air pollution, was a 25% increase compared to 2000 data (883,100).

Premature deaths attributable to ambient $PM_{2.5}$ varied substantially across China (Fig. 2), and the regions with higher mortality density are usually those with abundant air pollutant emissions (e.g., Hebei), populations (e.g., Henan), or both (e.g., Jiangsu). The top five provinces with negative health impacts were respectively Henan (109,300 premature deaths), Shandong (103,800), Jiangsu (84,300), Hebei (78,500), and Sichuan (75,900), which together accounted for 41% of China's premature deaths attributable to ambient $PM_{2.5}$ in 2007. As in previous estimates (Xie et al., 2016), Hebei was among the top five Chinese provinces with respect to death risk (i.e., per capita premature death) and health burden (i.e., premature death per unit of local GDP) in 2007. The premature deaths attributed to ambient air pollution in Beijing were 18,400, with a death risk around 1200 deaths per million, or 30% higher than China's national average.

3.2. Health impact of emissions related to domestic trade

Previous studies (Lin et al., 2014; Wang et al., 2017; Zhang et al., 2017; Zhao et al., 2017) have shown the complexity of regional air pollution issues, which need to be addressed by comprehensive consideration of supply chains, atmospheric transport and chemistry, and population distribution. In this study, Beijing and Hebei were taken as

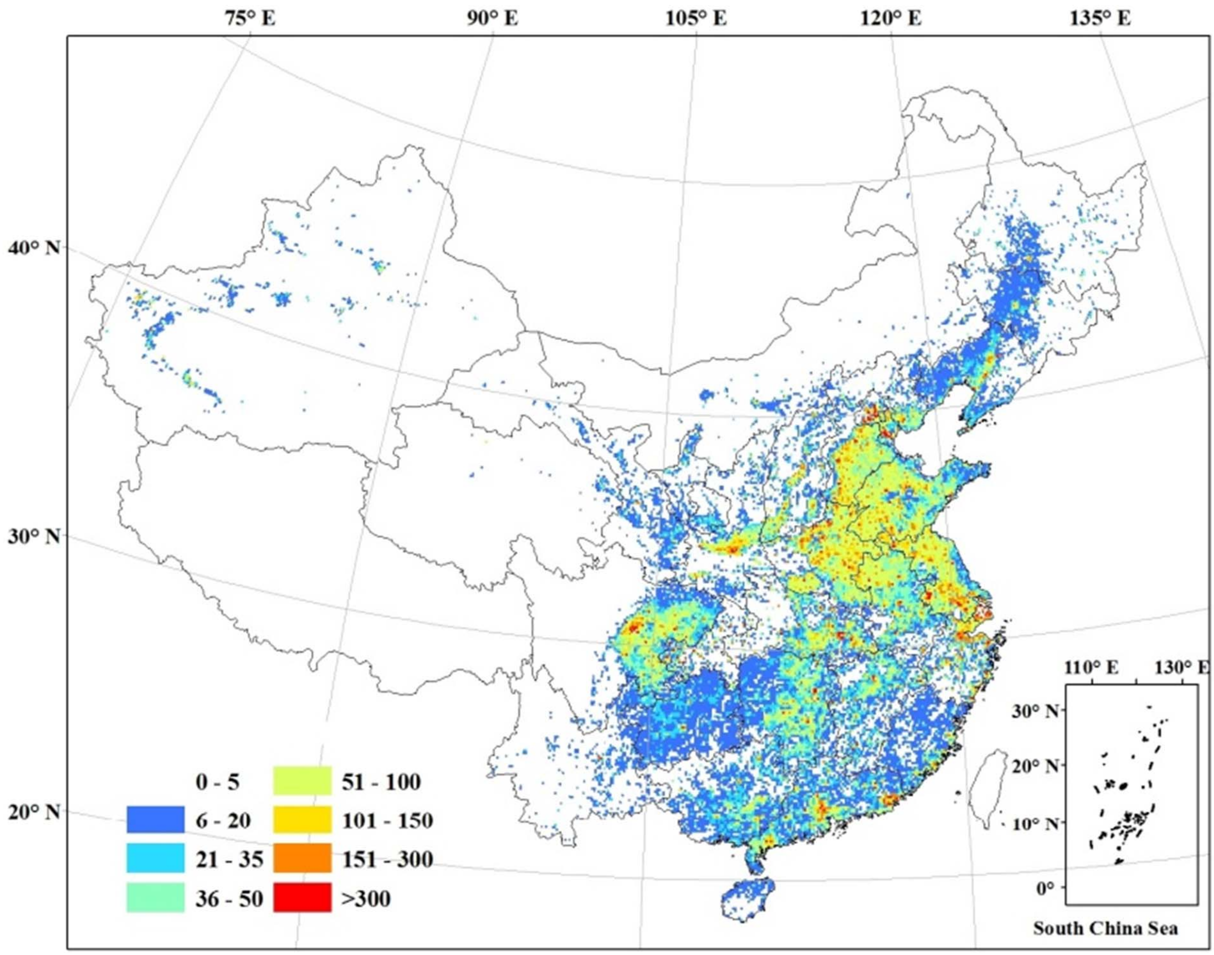

Fig. 2. Gridded premature deaths attributable to ambient $PM_{2.5}$ across China in 2007. The premature deaths are calculated for each grid cell at a resolution of 10 km × 10 km and are aggregated for each Chinese province.

examples to illustrate the impacts of atmospheric transport and domestic supply chains on public health across China.

In 2007, premature deaths due to emissions relating to exports from Beijing and Hebei were 2200 and 37,900 respectively (Fig. 3a and d). Although these emissions originated within Beijing and Hebei, their related health impacts were not limited to these regions, but spread beyond their geographical boundaries to other provinces across China. Because such spillovers of health impacts are mainly caused by cross-border atmospheric transport of air pollution, they are usually severe in neighboring provinces and become weaker with distance. For example, 19% (3400) and 16% (2100) of premature deaths in the neighboring metropolis of Beijing and Tianjin could be attributed to emissions related to inter-provincial exports from Hebei to other provinces (including Beijing and Tianjin), but the impacts in the faraway provinces of Guangdong and Yunnan were negligible. Because production-based emissions include export-related emissions and also originate within regional geographical boundaries, their health impacts (Fig. 3e and f) are higher (e.g., 8200 premature deaths related to production-based emissions, or nearly four times those from emissions related to exports from Beijing), but with similar geographical distribution characteristics to those of export-related emissions (Fig. 3a and d).

The premature deaths attributed to emissions related to domestic imports from other provinces to Beijing and Hebei were 16,500 and 14,500 respectively in 2007. Because one region might import goods and materials to support its own consumption far away from the other producing provinces (Wang et al., 2017), health impacts attributed to emissions related to Beijing and Hebei's imports are much broader (covering almost all provinces) (Fig. 3c and d) than those related to exports and production. This reflects the complexity of supply chains among the Chinese provinces, which make the health impact related to emissions embodied in domestic trade even broader than the atmospheric cross-border transport of air pollution (Zhao et al., 2017).

3.3. Production- and consumption-based health impacts

In 2007, air pollutant emissions from production within Beijing's geographical boundary caused 8200 premature deaths (Fig. 4), which were mainly distributed within its own boundary and in neighboring provinces (e.g., Hebei) (Fig. 3c). Such production-based health impacts were much lower than its regional premature deaths (18,400) attributable to air pollution, reflecting the great influence of cross-border air pollution flows on Beijing (Fig. 3f). For example, 36% of ambient $PM_{2.5}$ in Beijing has been reported to be transferred from other regions outside Beijing (Xue et al., 2014). As China's capital and one of the world's largest cities, Beijing imports a large quantity of goods, especially pollution-intensive ones, from other domestic provinces to support local consumption. For example, SO_2 emissions due to Beijing's imports from other provinces were nearly eight times those embodied in exports from Beijing (Zhang et al., 2015), thus causing greater health impacts (16,500 premature deaths) due to emissions related to imports to Beijing from other provinces (Fig. 3b). This explains why consumption-based health impacts (22,500 premature deaths) of Beijing were nearly three times the production-based impacts and 20% higher than regional premature deaths due to ambient air pollution.

Similarly to Beijing, Hebei's premature deaths were also greatly influenced by other regions through cross-border atmospheric transport

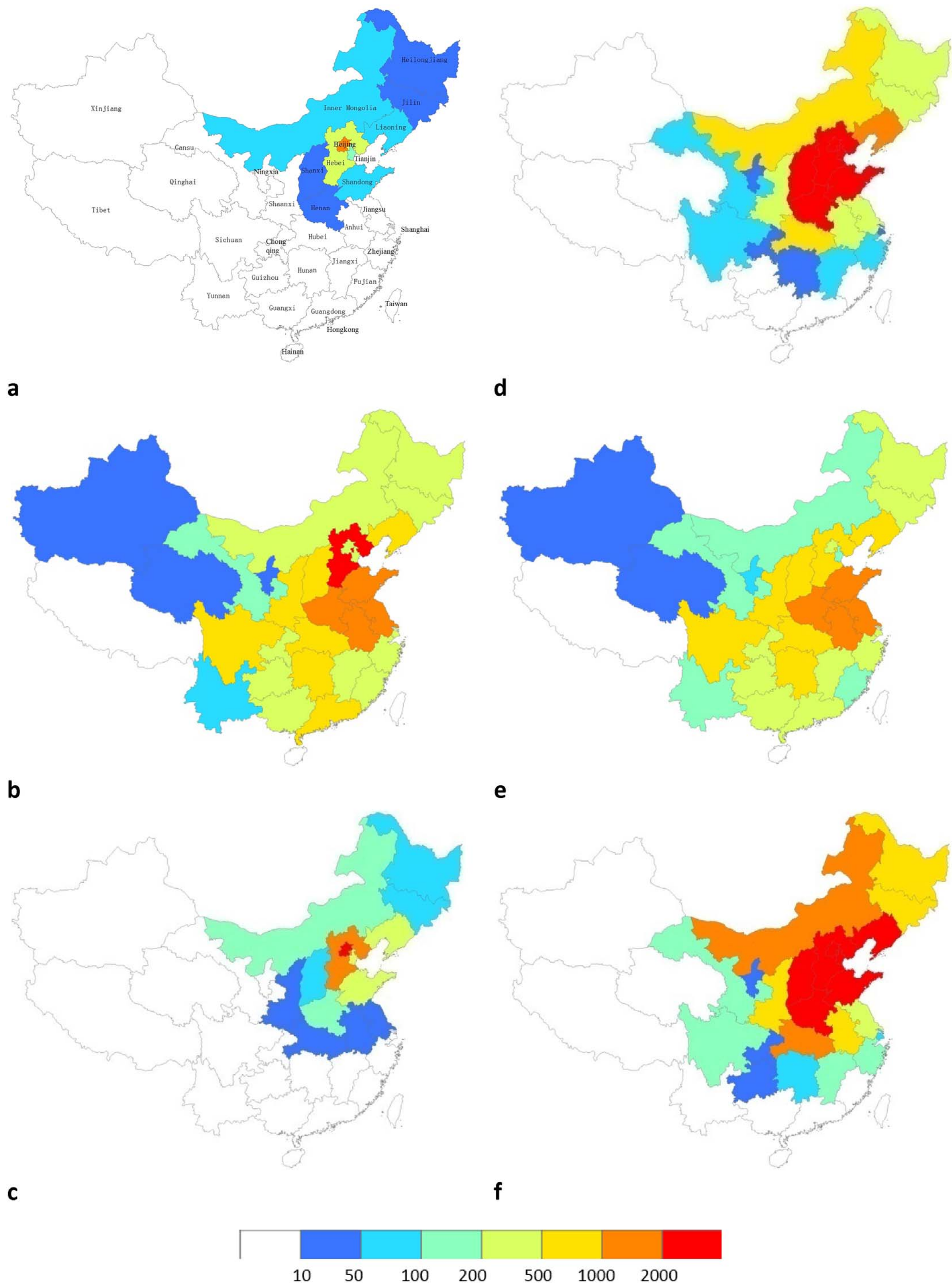

Fig. 3. Premature deaths attributable to air pollutant emissions embodied in domestic trade between Chinese provinces. Fig. 3a and d show deaths attributable to emissions relating to interprovincial exports *from* Beijing and Hebei to other provinces respectively. Fig. 3b and e show deaths attributable to emissions related to interprovincial imports *to* Beijing and Hebei respectively from other provinces. Fig. 3c and f show the deaths related to production-based emissions (i.e., emissions within the geographical boundary) of Beijing and Hebei respectively.

of air pollution (Fig. 3c). Consumption in Hebei was found to account for 49,700 premature deaths, which was 30%–40% lower than the number of regional and production-based premature deaths. The reason for this is that Hebei is a net exporter in China's domestic supply chain, and 51% of its production-based premature deaths were caused by emissions related to consumption in other provinces (Fig. 3d).

Note that the health impacts caused by *emissions* related to the domestic imports and exports of a region cannot be simply equated to the effects of *trade* on a region's health impact. In this research, the health impacts caused by emissions related to production, interprovincial exports, and imports were separately evaluated (Eq. (8)), and the consumption-based health impacts for individual provinces were calculated (Eq. (9)). Such consumption-based assessment reapportions the health impacts of air pollution based on consumption (e.g., adding those impacts attributable to imports and subtracting those due to exports), but contains an implicit assumption that China's total mortality related to air pollution (i.e., 1.10 million premature deaths) would be conserved if international trade were not considered. This approach has now been

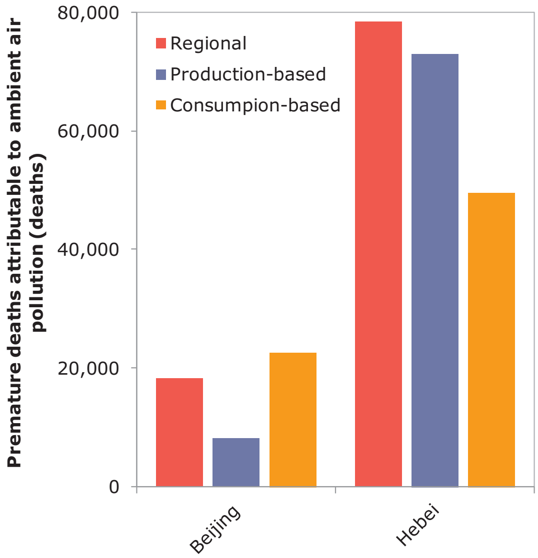

Fig. 4. Provincial premature deaths attributable to ambient $PM_{2.5}$ from various perspectives. "Regional" means premature deaths related to ambient $PM_{2.5}$ occurring within the geographical boundaries of Beijing and Hebei respectively (as shown in Fig. 2). "Production-based" means premature deaths related to a region's production-based emissions (as shown in Fig. 3c and f). "Consumption-based" means premature deaths related to a region's consumption-based emissions. For example, the consumption-based health impacts of Beijing could be estimated as "results c" + "results b" − "results a" in Fig. 3. Because the proposed model cannot evaluate premature deaths embodied in imports from outside China, the "consumption-based health impacts" of Beijing and Hebei are defined here to include only impacts within China and not those from or in other countries.

applied in a number of analyses contrasting regional consumption- and production-based emissions of greenhouse gases and air pollutants (e.g., Huo et al., 2014 and Feng et al., 2013). Such a calculation of consumption-based premature deaths overlooks a change in the total health impact attributable to air pollution and hence would not capture the effects (either beneficial or harmful) of trade on public health across China. Regional consumption would be satisfied by each region's own production, assuming no trade among Chinese provinces. Therefore, total emissions would be re-allocated to each province according to the consumption of each, but consistently with real total emissions in China. Based on such re-allocated emissions, the variations in China's provincial and general air quality and the related health impacts compared to real impacts could be assumed to be the effects of domestic trade on public health due to air pollution across China (Wang et al., 2017).

These calculations of regional consumption-based health impacts do not include premature deaths due to international trade because the proposed model cannot evaluate the premature deaths embodied in imports from outside China. This means that neither premature deaths due to emissions embodied in provincial exports to other countries, nor premature deaths due to emissions embodied in provincial imports from other countries have been calculated. Because the embodied emissions in China's exports are much higher than those in its imports, coupled with the higher population density in China, the total health impacts resulting from emissions related to imports to China will be considerably less than those related to its exports. Therefore, this study will tend to overestimate consumption-based health impacts of Beijing and Hebei.

4. Conclusion

We have proposed an approach for quantifying the health impacts of emissions due to regional consumption, and applied it to Beijing and Hebei province in China. The consumption-based premature deaths attributable to ambient $PM_{2.5}$ of Beijing and Hebei were respectively 22,500 and 49,700 in 2007, which were respectively 23% higher and 37% lower than the numbers solely within their boundaries. The large and broad impacts of domestic trade on regional air quality and public health disclosed in this study suggests the need to take into account the full supply chains, not just the areas of production, in designing policy to mitigate the negative health impacts of air pollution across China. The value of this paper is thus an improved methodology that considers health impacts of emissions related to a region's consumption, not just production, to take account of the large inter-provincial trade in China. The approach established here could also be applied in other regions around the world.

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