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Identifying critical supply chain paths and key sectors for mitigating primary carbonaceous $PM_{2.5}$ mortality in Asia

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ABSTRACT

Total mortality attributable to $PM_{2.5}$ is highest in the Asian domain, estimated as 2.3 million deaths annually. We apply consumption-based accounting to identify the key sectors responsible for primary carbonaceous $PM_{2.5}$ mortality. The study combines an input–output model with an atmospheric transport model and fully links consumer demand to final pollutant fate and health impact. We find the following: (1) considering atmospheric transport changes the distribution of demand-induced impact as compared to conventional emissions footprinting, (2) the supply chain paths with the greatest impact on $PM_{2.5}$-induced human health problems in the region are centered around agricultural technologies in China, and (3) the transportation sector of China plays a major role in the supply chain paths that generate relatively large impacts on human health. We conclude that Japan is responsible for $PM_{2.5}$ mortality in Asia and should take leadership in changing key high-priority technologies and critical supply chain paths into greener ones.

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$PM_{2.5}$-induced health impact; cross-border pollution; key sector analysis; structural path analysis; multi-regional input–output analysis

1. Introduction

Asia produces almost half of all global manufactured goods and plays a vital role as a global production powerhouse (*The Economist*, 2015). As the industrial production of the region continues to rise, so do concerns about the adverse environmental and health impacts associated with production activities. Among these, fine particulate matter ≤ 2.5 micrometers in aerodynamic diameter ($PM_{2.5}$) has been one of the most controversial environmental and human health issues in this region in recent years (Pope and Dockery, 2006; Pope et al., 2009; Anenberg et al., 2011; Lepeule et al., 2012). It has been estimated that both per-capita and total mortality attributable to $PM_{2.5}$ are highest in the Asian domain, amounting to 63 deaths per 100,000 population and 2.3 million total deaths, respectively, in 2010 (Apte et al., 2015).

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Recent studies using consumption-based accounting have shown that a large proportion of the $PM_{2.5}$ emissions in China is induced by consumer demand in China (Guan et al., 2014; Huo et al., 2014; Lin et al., 2014; Takahashi et al., 2014; Meng et al., 2016). Guan et al. (2014) measured consumption-based emissions of primary $PM_{2.5}$ utilizing an inventory of air pollutant emissions in China to understand the main driving forces behind the emissions and also found that $PM_{2.5}$ emissions embodied in Chinese exports are mainly triggered by consumption in OECD countries. The emission of primary $PM_{2.5}$ and $PM_{2.5}$ precursors originally emitted in China then transported to neighboring countries via prevailing westerly winds has been a source of diplomatic conflicts in the region (Ohara et al., 2007). Takahashi et al. (2014) further combined the consumption-based accounting with an atmospheric transport model (Nishizawa et al., 2012) and analyzed the $PM_{2.5}$-induced 'mortality impacts' in terms of primary black carbon (BC) and primary organic carbon (OC) – both major constituents of $PM_{2.5}$ – by country and by sector of the economy.

Traditional footprinting exercises, including the original work by Leontief (Leontief, 1970; Leontief and Ford, 1971) linking consumer demand to air pollution, connect demand to a resource demand or pollution flux. This approach has been called a 'pressure footprint', standing in contrast to an 'impact footprint' in which demand is linked to actual environmental impact (Verones et al., Forthcoming). These concepts are clearly classified in the so-called DPSIR (Driving forces, Pressures, States, Impacts, and Responses) framework (Smeets and Weterings, 1999) used in the EU to form environmental policy.

An effective $PM_{2.5}$ pollution mitigation strategy can benefit from targeted understanding of the key supply chains that drive $PM_{2.5}$ emissions. As increasingly more intermediate products are crossing national borders in the course of the expansion of international trade, however, understanding the structure of the supply chains that induce $PM_{2.5}$ emissions and $PM_{2.5}$-induced mortality is a challenge.

Previous studies have not determined environmentally important supply chains that have great potential to effectively reduce the health impacts in polluted countries. In this study, we use the environmentally extended Asian input–output table of 2005 and apply a comprehensive economic network analysis including key sector analysis (Rasmussen, 1956; Hirschman, 1958; Hazari, 1970; Lenzen, 2003) and structural path analysis (SPA) (Treloar, 1997; Lenzen, 2002; 2003; 2007; Peters and Hertwich, 2006a; 2006b; Suh and Heijungs, 2007; Minx et al., 2008; Lenzen and Murray, 2010; Skelton et al., 2011; Kagawa et al., 2015; Meng et al., 2015) to identify the environmentally important supply chain paths and key industries that contribute to the 'primary carbonaceous' $PM_{2.5}$ emissions of the region. A novelty of this study is that we introduced an atmospheric transport model in order to fully link consumer demand via supply chains to primary emitters, and then link those emitters via atmospheric transport to fate and health impact.

The remainder of this paper is structured as follows: Section 2 explains our methodology, Section 3 describes the data, Section 4 presents and discusses the results, and finally Section 5 offers discussion and conclusions.

2. Methods

2.1. Consumption-based $PM_{2.5}$ emissions

The output vector $\mathbf{x} = (x_i^r)$ $(r = 1, \ldots, M, i = 1, \ldots, N)$ in a multi-regional input–output analysis with N industries and M countries can be expressed as a linear equation:

$\mathbf{x} = \mathbf{Ax} + \mathbf{f}$, where $\mathbf{f} = (f_j^s)$ is the final demand vector, representing the final global demand for the products of industry j of country s, and $\mathbf{A} = (Z_{ij}^{rs}/x_j^s) = (a_{ij}^{rs})$ is an input coefficient matrix, expressing the intermediate input for industry i of country r that is necessary per unit of production of the product of industry j of country s, for which Z_{ij}^{rs} represents the intermediate input into industry j of country s from industry i of country r. Final demand vector $\mathbf{f}$ can be expressed as the sum of the final demand vectors of each demand country as $\mathbf{f} = \mathbf{f}^1 + \mathbf{f}^2 + \cdots + \mathbf{f}^M = \sum_{s=1}^{M} \mathbf{f}^s$, where $\mathbf{f}^s$ is the domestic final demand vector of country s. Solving the above linear equation for output vector $\mathbf{x}$, we obtain the following equation:

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{f} = \mathbf{Lf}, \tag{1}$$

where $\mathbf{I}$ is the identity matrix and $\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1} = (L_{ij}^{rs})$ is the Leontief inverse matrix with elements L_{ij}^{rs} expressing the output of industry i of country r that is directly and indirectly needed to satisfy one unit of final demand from industry j of country s.

If the direct emission intensity vector that contains primary BC and OC particulate emissions ($PM_{2.5}$ emissions in short hereafter) per unit output of industry i of country r is defined as $\mathbf{d} = (d_i^r)$, then consumption-based $PM_{2.5}$ emissions can be estimated as follows:

$$\mathbf{e}^{s^*} = \hat{\mathbf{d}}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{f}^{s^*} = \hat{\mathbf{d}}\mathbf{L}\mathbf{f}^{s^*}, \tag{2}$$

where $\hat{\mathbf{d}}$ is the diagonalization of $\mathbf{d}$, and $\mathbf{f}^{s^*}$ is the final demand vector of s^*. An element e_i^r of $\mathbf{e}^{s^*}$ represents the $PM_{2.5}$ emissions induced by industry i of country r associated with final demand in demand country s^*.

2.2. Consumption-based health impacts

The relationship data defining how much of the $PM_{2.5}$ emitted within a source country is carried to another, receptor country and impacts the health of the people of the receptor country are given by the source–receptor relationship (SRR) matrix $\mathbf{Q} = (q_i^{wr})$. The SRR matrix element q_i^{wr} represents the number of premature deaths in country w caused per unit of $PM_{2.5}$ emitted by industry i of country r. By combining the SRR matrix with Equation 2, $\mathbf{m}_1^{s^*}$, the number of premature deaths in each country w due to $PM_{2.5}$ emissions from each industry i of each country r associated with final demand in country s^*, can be estimated using the following equation:

$$\mathbf{m}_1^{s^*} = \mathbf{Q}\hat{\mathbf{d}}\mathbf{L}\mathbf{f}^{s^*} = \mathbf{Q}\mathbf{e}^{s^*}. \tag{3}$$

A vector element of $\mathbf{m}_1^{s^*}$ represents the number of premature deaths in each country w induced by final demand in country s^*.

The quantity of territorial and cross-border pollution associated *directly* with $PM_{2.5}$ emissions from the household sector of country s^* can be estimated similarly using the SRR matrix $\mathbf{h}^{s^*} = (h^{ws^*})$ for the household sector, as $\mathbf{m}_2^{s^*} = \mathbf{h}^{s^*} g^{s^*}$, where the SRR vector element h^{ws^*} expresses the number of premature deaths in country w due to the cross-border pollution of one unit of $PM_{2.5}$ directly emitted from the household sector of country s^*, and g^{s^*} denotes the total $PM_{2.5}$ emissions from the activities (burning of coal and biomass for heating, use of diesel vehicles and gasoline-powered cars, etc.) of the household sector of country s^*. By adding the number of premature deaths in country w arising from indirect emissions due to final demand in country s^* to the number of premature deaths in each country w arising from direct emissions from the household sector of country s^*, we can estimate the direct and indirect impact of emissions in country s^* on health in each country w as $\mathbf{m}_s^* = \mathbf{m}_1^{s^*} + \mathbf{m}_2^{s^*}$.

2.3. Identifying key sectors

The matrix $\hat{\mathbf{d}}\mathbf{L}$ on the right-hand side of Equation 3 shows the direct and indirect $PM_{2.5}$ emissions associated with output of industry i of country r needed to satisfy one unit of final demand from industry j of country s, and therefore it can also be defined as $\hat{\mathbf{d}}\mathbf{L} = \mathbf{E} = (E_{ij}^{rs})$. Following previous work (Rasmussen, 1956; Hirschman, 1958; Hazari, 1970; Lenzen, 2003; Ma et al., 2012), the two indices of power of dispersion (i.e. backward linkages) in industry j of country s and sensitivity of dispersion (i.e. forward linkages) in industry i of country r can be defined as

$$PD_j^s = \frac{\sum_{r=1}^{M}\sum_{i=1}^{N} E_{ij}^{rs}}{\frac{\sum_{s=1}^{M}\sum_{j=1}^{N}\sum_{r=1}^{M}\sum_{i=1}^{N} E_{ij}^{rs}}{M\times N}}, \tag{4}$$

and

$$SD_i^r = \frac{\sum_{s=1}^{M}\sum_{j=1}^{N} E_{ij}^{rs}}{\frac{\sum_{r=1}^{M}\sum_{i=1}^{N}\sum_{s=1}^{M}\sum_{j=1}^{N} E_{ij}^{rs}}{M\times N}}, \tag{5}$$

respectively. If the backward linkage effect of industry j of country s (i.e. $\sum_{r=1}^{M}\sum_{i=1}^{N} E_{ij}^{rs}$ in the numerator of Equation 4) is larger than the global average across industries and countries (i.e. $\sum_{s=1}^{M}\sum_{j=1}^{N}\sum_{r=1}^{M}\sum_{i=1}^{N} E_{ij}^{rs}/(M \times N)$ in the denominator of Equation 4), the power of dispersion in Equation 4 is larger than one, and vice versa. In other words, sectors with higher power of dispersion indices (thus exceeding 1.0) are environmentally important sectors in the sense that $PM_{2.5}$ is relatively heavily emitted through the entire backward supply chains in the Asian countries associated with one unit of final demand of the specific sector. Similarly, sectors with higher sensitivity of dispersion indices (thus exceeding 1.0) are also environmentally important sectors in the sense that $PM_{2.5}$ is relatively heavily emitted by producing and supplying products of the specific sector to satisfy one unit of final demand of all the sectors across countries. A key sector can be found by checking the conditions $PD_j^s > 1$ and $SD_i^r > 1$ (Lenzen, 2003). The key sector exhibits both above-average influence and dependence on other sectors regarding $PM_{2.5}$ emissions.

A similar key sector analysis is applied to the consumption-based health impacts. Noting that, from the SRR matrix $\mathbf{Q} = (q_i^{wr})$, the *total* number of premature deaths in all the countries caused per unit of $PM_{2.5}$ emitted by industry i of country r is defined as $\mathbf{q} = (q_i^r) = \sum_{w=1}^{M} q_i^{wr}$, the direct and indirect premature deaths associated with output of industry i of country r needed to satisfy one unit of final demand from industry j of country s can be defined as $\hat{\mathbf{q}}\hat{\mathbf{d}}\mathbf{L} = \mathbf{G} = (G_{ij}^{rs})$. Substituting G_{ij}^{rs} into E_{ij}^{rs} on the right-hand side of Equations 4 and 5 yields the two indices, power of dispersion and sensitivity of dispersion, which in this case are denoted $\widetilde{PD}_j^s$ and $\widetilde{SD}_i^r$, respectively.

As Lenzen (2003) noted, the indices $PD_j^s(\widetilde{PD}_j^s)$ and $SD_i^r(\widetilde{SD}_i^r)$ ignore the relative importance of sectoral final demand that plays a crucial role in consumption-based accounting.

A natural way of addressing this deficit is to define weighted indices of power of dispersion and sensitivity of dispersion as

$$PD_j^{s*} = \frac{\sum_{r=1}^{M} \sum_{i=1}^{N} \alpha_j^s E_{ij}^{rs}}{\frac{\sum_{s=1}^{M} \sum_{j=1}^{N} \sum_{r=1}^{M} \sum_{i=1}^{N} \alpha_j^s E_{ij}^{rs}}{M \times N}}, \tag{6}$$

and

$$SD_i^{r*} = \frac{\sum_{s=1}^{M} \sum_{j=1}^{N} \alpha_j^s E_{ij}^{rs}}{\frac{\sum_{r=1}^{M} \sum_{i=1}^{N} \sum_{s=1}^{M} \sum_{j=1}^{N} \alpha_j^s E_{ij}^{rs}}{M \times N}}, \tag{7}$$

respectively, where α_j^s denotes the portion of final demand of products produced by industry j of country s among the total of final demand across industries and countries. Regarding $\widetilde{PD}_j^s$ and $\widetilde{SD}_i^r$, we can similarly define the corresponding weighted indices as $\widetilde{PD}_j^{s*}$ and $\widetilde{SD}_i^{r*}$, respectively.

2.4. Identifying critical supply chain paths

Here, we identify the environmentally important supply chain paths by evaluating the contribution made by the supply chain paths linking consumption and production to the consumption-based $PM_{2.5}$ emissions and cross-border pollution obtained above. If we perform a series expansion of the Leontief inverse matrix of Equation 1, we obtain $\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1} = \mathbf{I} + \mathbf{A} + \mathbf{A}^2 + \mathbf{A}^3 + \ldots$. Then, from Equation 2, we can solve for the $PM_{2.5}$ emissions arising from consumption in country s^* as follows:

$$\mathbf{e}^{s^*} = \hat{\mathbf{d}}\mathbf{f}^{s^*} + \hat{\mathbf{d}}\mathbf{A}\mathbf{f}^{s^*} + \hat{\mathbf{d}}\mathbf{A}^2\mathbf{f}^{s^*} + \hat{\mathbf{d}}\mathbf{A}^3\mathbf{f}^{s^*} + \cdots. \tag{8}$$

If, for example, final demand for a particular product is generated in country s^*, then the quantity of $PM_{2.5}$ emitted in the supplying country at the production stage to satisfy that demand is $\hat{\mathbf{d}}\mathbf{f}^{s^*}$.

Furthermore, $\mathbf{A}\mathbf{f}^{s^*}$ denotes intermediate goods needed to meet the final demand, and they yield a quantity of $PM_{2.5}$ emissions $\hat{\mathbf{d}}\mathbf{A}\mathbf{f}^{s^*}$. Through a series expansion of the Leontief inverse matrix, this emissions process continues infinitely. Thus, the element e_i^{rs*} for computing $\mathbf{e}^{s^*}$ can be estimated by the following equation:

$$\begin{aligned}
e_i^{rs*} &= \sum_{v=1}^{M} \sum_{j=1}^{N} d_i^r (I_{ij}^{rv} + a_{ij}^{rv} + (\mathbf{A}^2)_{ij}^{rv} + (\mathbf{A}^3)_{ij}^{rv} + \cdots) f_j^{vs*} \\
&= \sum_{v=1}^{M} \sum_{j=1}^{N} d_i^r \left(I_{ij}^{rv} + a_{ij}^{rv} + \sum_{t=1}^{M} \sum_{k=1}^{N} a_{ik}^{rt} a_{kj}^{tv} + \sum_{u=1}^{M} \sum_{t=1}^{M} \sum_{l=1}^{N} \sum_{k=1}^{N} a_{il}^{ru} a_{lk}^{ut} a_{kj}^{tv} + \cdots \right) f_j^{vs*} \\
&= d_i^r f_i^{rs*} + \sum_{t=1}^{M} \sum_{j=1}^{N} d_i^r a_{ij}^{rv} f_j^{vs*} + \sum_{t=1}^{M} \sum_{r=1}^{M} \sum_{j=1}^{N} \sum_{k=1}^{N} d_i^r a_{ik}^{rt} a_{kj}^{tv} f_j^{vs*} \\
&\quad + \sum_{u=1}^{M} \sum_{t=1}^{M} \sum_{r=1}^{M} \sum_{j=1}^{N} \sum_{k=1}^{N} \sum_{l=1}^{N} d_i^r a_{il}^{ru} a_{lk}^{ut} a_{kj}^{tv} f_j^{vs*} + \cdots,
\end{aligned} \tag{9}$$

where i, j, k, and l are industrial indices and r, s, t, u, and v are regional indices. I_{ij}^{rv} takes value 1 when $r = v$ and $i = j$, and is otherwise 0. The first term on the right-hand side of Equation 9, $d_i^r f_i^{rs^*}$, denotes the PM$_{2.5}$ emissions of industry i of country r induced by final demand in country s^*. The second term, $d_i^r a_{ij}^{rv} f_j^{vs^*}$, expresses the PM$_{2.5}$ emissions induced by the production of the intermediate goods of industry i of country r that is needed for the products produced by industry j of country v in order to satisfy the final demand in country s^*. The third term, $d_i^r a_{ik}^{rt} a_{kj}^{tv} f_j^{vs^*}$, represents the emissions resulting from the supply chain path 'final demand in country s^*' → 'production of industry j of country v' → 'production of industry k of country t' → 'production of industry i of country r'.

Similarly, the element m^{ws^*} for computing $\mathbf{m}_1^{s^*}$ showing the consumption-based health impacts can be estimated by the following equation:

$$
\begin{aligned}
m^{ws^*} &= \sum_{r=1}^{M}\sum_{i=1}^{N}\sum_{v=1}^{M}\sum_{j=1}^{N} q_i^{wr} d_i^r \left(I_{ij}^{rv} + a_{ij}^{rv} + (\mathbf{A}^2)_{ij}^{rv} + (\mathbf{A}^3)_{ij}^{rv} \cdots\right) f_j^{vs^*} \\
&= \sum_{r=1}^{M}\sum_{i=1}^{N}\sum_{v=1}^{M}\sum_{j=1}^{N} q_i^{wr} d_i^r \left(I_{ij}^{rv} + a_{ij}^{rv} + \sum_{t=1}^{M}\sum_{k=1}^{N} a_{ik}^{rt} a_{kj}^{tv} \right. \\
&\qquad \left. + \sum_{u=1}^{M}\sum_{t=1}^{M}\sum_{l=1}^{N}\sum_{k=1}^{N} a_{il}^{ru} a_{lk}^{ut} a_{kj}^{tv} + \cdots \right) f_j^{vs^*} \\
&= \sum_{r=1}^{M}\sum_{i=1}^{N} q_i^{wr} d_i^r f_i^{rs^*} + \sum_{r=1}^{M}\sum_{i=1}^{N}\sum_{v=1}^{M}\sum_{j=1}^{N} q_i^{wr} d_i^r a_{ij}^{rv} f_j^{vs^*} \\
&\quad + \sum_{r=1}^{M}\sum_{i=1}^{N}\sum_{t=1}^{M}\sum_{k=1}^{N}\sum_{v=1}^{M}\sum_{j=1}^{N} q_i^{wr} d_i^r a_{ik}^{rt} a_{kj}^{tv} f_j^{vs^*} + \cdots
\end{aligned}
\tag{10}
$$

The second term on the right-hand side of Equation 10, $q_i^{wv} d_i^r a_{ij}^{rv} f_j^{vs^*}$, quantitatively expresses the health impacts on country w due to PM$_{2.5}$ emitted by the production of intermediate goods by industry i of country r that is necessary for the products produced by industry j of country v in order to satisfy final demand in country s^*. In other words, from the second term on the right-hand side of Equation 10, it is possible to quantify supply chain paths such as 'final demand in country s^* (i.e. consumption driver country)' → 'industry j of country v (transmission country)' → 'industry i of country r (emission source country)' → 'health impacts on country w (impact receptor country)'.

3. Data and computation

We used the Asian International Input–Output Table (AIIOT) for 2005 provided by the Institute of Developing Economies Japan of the External Trade Organization (IDE-JETRO). AIIOT is a multi-regional input–output table covering 10 countries and regions (Indonesia (IDN), Malaysia (MYS), the Philippines (PHL), Singapore (SGP), Thailand (THA), China (CHN), Taiwan (TWN), South Korea (KOR), Japan (JPN), and the United States (USA)) and 76 industry sectors (see Table S1 of *Supporting information* (SI)). This study thus considers 760 specific sectors.

Considering that there are 760 sectors in our input–output framework, the computation for key sector analysis formulated by Equations 4 and 5 or Equations 6 and 7 is relatively easy compared to the huge computation for the SPA formulated by Equations 9 and/or 10. The number of supply chain paths in the first tier expressed by the first term on the right-hand side of Equation 10 is $76 \times 10 = 760$, the number of paths in the second tier is $760^2 = 577,600$, and the number in the nth tier is 760^n. However, the contribution of total emissions at a given tier rapidly declines as the tier number increases. For the purposes of this study, therefore, we set a threshold in order to disregard supply chain paths that account for less than 0.001% of total $PM_{2.5}$ emissions. As a result, our computation only considers paths up to the 10th tier.

This study also makes use of data on $PM_{2.5}$ emissions by sector and SRR matrix in accordance with the international input–output table for Asia estimated by our previous study (see Tables S2–S14 of SI). It should be noted that the SRR matrix was estimated by using an atmospheric transport model with a focus on the Asian countries (Skamarock et al., 2008; Nishizawa et al., 2012). Modeling simulations were conducted using the Weather Research and Forecasting modeling technique (Skamarock et al., 2008) and the Community Multiscale Air Quality (CMAQ) modeling system (Byun and Schere, 2006) with Regional Emission inventory in ASia (Ohara et al., 2007) to determine the yearly averaged regional concentrations of BC and OC emitted from four sectors (power plant, industry, transport, and agriculture) in East and Southeast Asia (Tables S12–S14 of SI). The human health effects (i.e. premature deaths in persons) arising from the pollution concentrations were estimated by using the concentration-response function (Environmental Benefits Mapping and Analysis Program, 2012), population-weighted annual mean concentration, annual baseline mortality rate, and exposed population. Since we could not obtain $PM_{2.5}$ emissions data and SRR data by US industry sector consistent with the industry classification of the AIIOT, the $PM_{2.5}$ emissions and health impacts in the United States associated with the final demand in other countries were not estimated in this study.

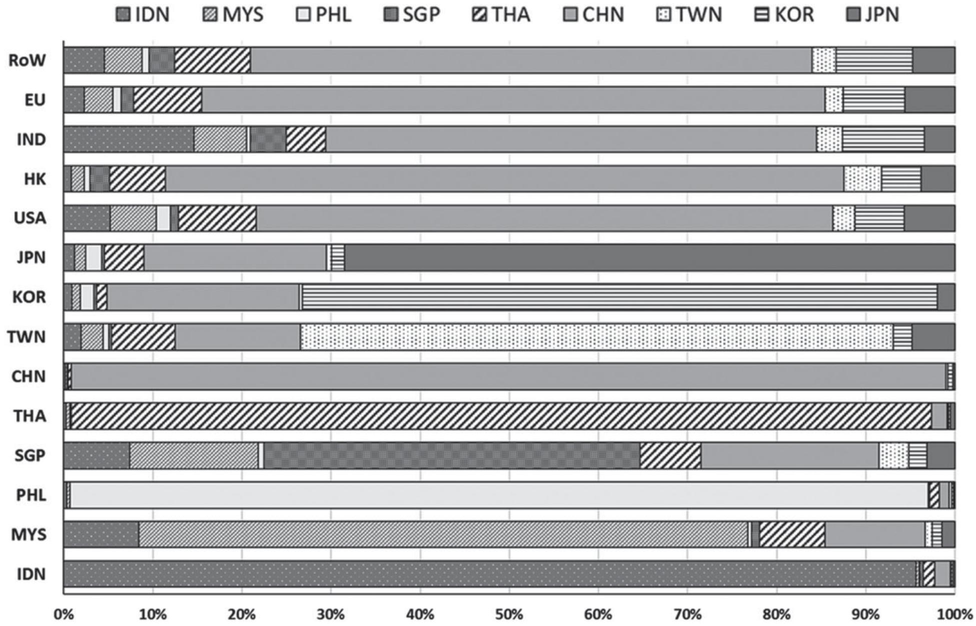
4. Results

4.1. Consumption-based analysis

We first calculated the consumption-based $PM_{2.5}$ emissions of a given driver country s^* using Equation 2. The total amount of the consumption-based $PM_{2.5}$ emissions in the major Asian nine countries (Indonesia, Malaysia, the Philippines, Singapore, Thailand, China, Taiwan, South Korea, and Japan) through the final demands of those countries, and the United States and exports to the rest of the countries and regions (Hong Kong, India, EU, and the rest of the world) was 1.6 million tonnes in 2005. China had the largest share of these consumption-driven emissions, driving 53% of total emissions, followed by Japan, Indonesia, and Thailand, contributing 8%, 7.5%, and 6.5%, respectively.

As in the embodied carbon transfer literature (e.g. Peters et al., 2011), a crucial question is whether the final demand in a specific driver country has affected $PM_{2.5}$ emissions in other Asian countries via international trade. From the result of consumption-based $PM_{2.5}$ emissions, we computed a breakdown of the $PM_{2.5}$ emissions in each source country associated with final demand in each driver country (Figure 1). Figure 1 shows that, of China's consumption-based emissions, 98% are generated within China (see Figure S1 in the SI for

Figure 1. $PM_{2.5}$ emissions (horizontal axis) from source countries driven by final demand in driver countries (vertical axis).



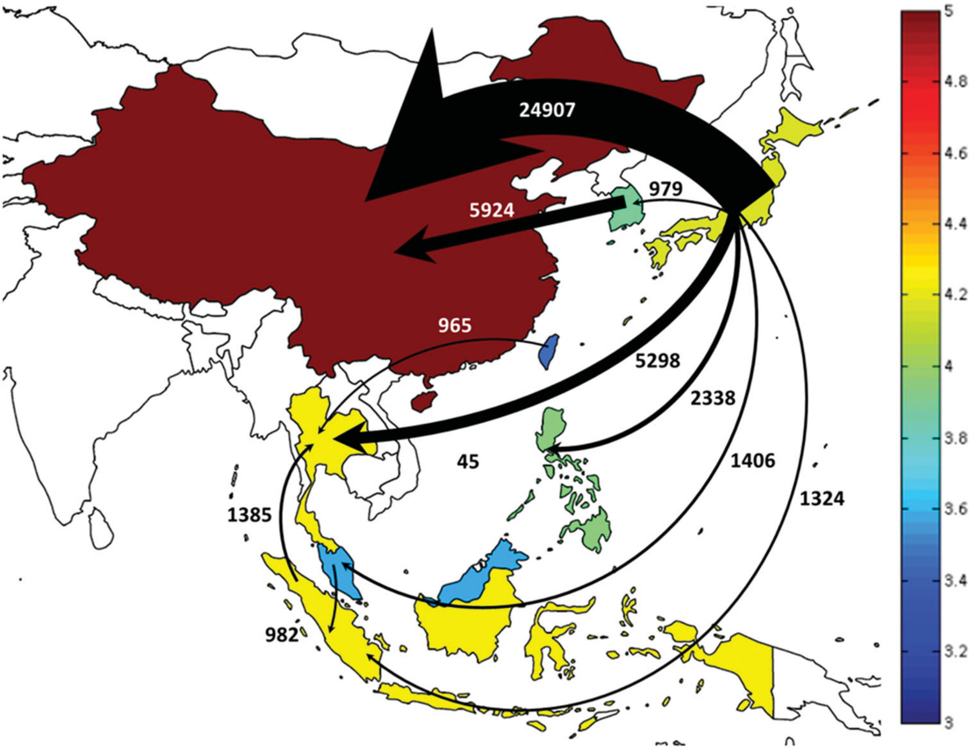
Note: Note that the $PM_{2.5}$ emissions in the United States are not included in this figure.

the consumption-based emissions). The $PM_{2.5}$ emissions of other countries induced by final demand in China (i.e. the emissions transfer of China) amount to just 16,000 tonnes, or a low 2% of consumption-based emissions, indicating that final consumers in China have a relatively low environmental impact on other Asian countries.

Using the results shown in Figure 1, the bilateral net emission transfer from country A to country B is easily calculable by $PM_{2.5}$ emissions of country B induced by final demand of country A minus $PM_{2.5}$ emissions of country A triggered by final demand of country B. A positive net emission transfer indicates that country A is more responsible for the emissions in country B. Figure 2 shows the $PM_{2.5}$ emissions of each country triggered by final demand of the nine Asian countries and the United States and net emission transfers arising from the consumption-based emissions. Figure 2 shows that Japan is currently transferring a large quantity, 32,789 tonnes, of its $PM_{2.5}$ emissions to other Asian countries. The biggest recipient of Japan's emissions transfer is China, which is followed by Thailand. Thus, Japan plays a crucial role in emitting $PM_{2.5}$ in Asia through the supply chains.

It is important to note that when addressing the health impact problem associated with $PM_{2.5}$ emissions, we need to distinguish between pollution within countries and cross-border pollution arising from consumption-based emissions. The health impacts (specifically, as measured by the number of premature deaths) due to consumption-based emissions can be estimated using Equation 3. First, we found that there were 26,000 premature deaths in total in the nine Asian countries for the year 2005, of which China accounted for 75%, demonstrating that China's final demand has an extremely large impact on air pollution in Asia.

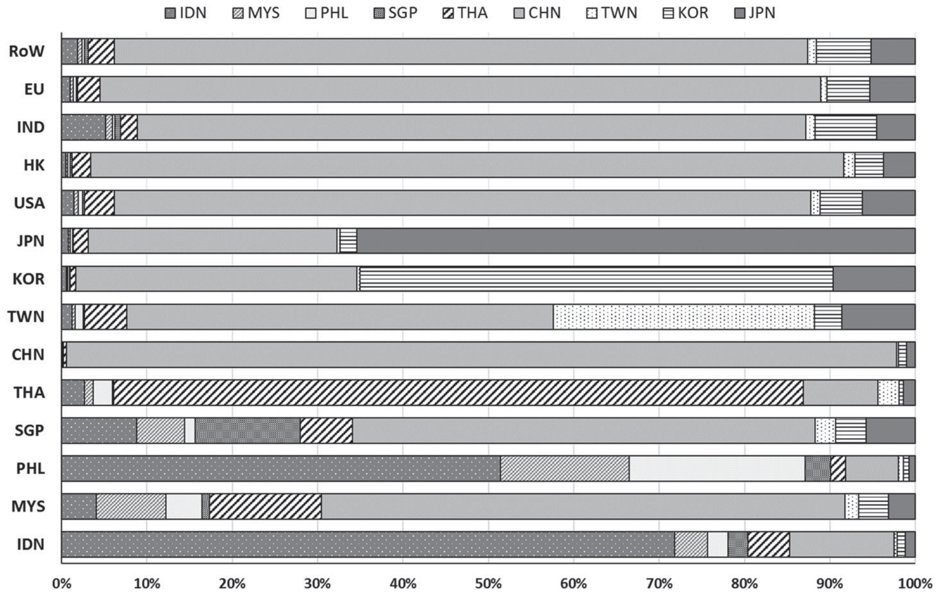
Figure 2. $PM_{2.5}$ emissions (tonnes) of each country triggered by final demand of the Asian nine countries and the United States and net emission transfers (tonnes) arising from the consumption-based emissions.



Note: The background color shows the common logarithms of the consumption-based emissions and the arrows show the top 10 bilateral net transfers of consumption-based emissions.

From Equation 3, we further estimated the number of premature deaths in each country due to cross-border $PM_{2.5}$ emissions associated with final demand in each country. Figure 3 shows a breakdown of the number of premature deaths in different receptor countries due to $PM_{2.5}$ emissions that originate from final demand in different driver countries (vertical axis). This figure clearly shows that the country most affected by $PM_{2.5}$ resulting from final demand in China is China itself. This is because almost all of the $PM_{2.5}$ originating from final demand in China is emitted within China, as shown by Figure 1. Of other Asian countries, Japan has the most premature deaths, those of 177 persons, attributable to $PM_{2.5}$ emissions originating from final demand in China, whereas the final demand of Japan led to the premature deaths of 644 persons in China. In other word, Japan transferred the $PM_{2.5}$-induced mortality amounting to the premature deaths of 468 persons to China (Figure 4). Looking at the consumption-based health impacts, South Korea also transferred approximately 126 premature deaths to China (Figure 4). Although it seems that the impact of cross-border pollution in South Korea and Japan due to $PM_{2.5}$ emissions generated in China is substantial, the health impact in China arising from $PM_{2.5}$ emissions associated with final demand in South Korea and Japan should also be paid more attention (Figure 4).

Figure 3. Premature deaths due to $PM_{2.5}$ emissions attributable to final demand in driver countries (vertical axis).



Note: Note that premature deaths due to $PM_{2.5}$ emissions in the United States are not included in this figure.

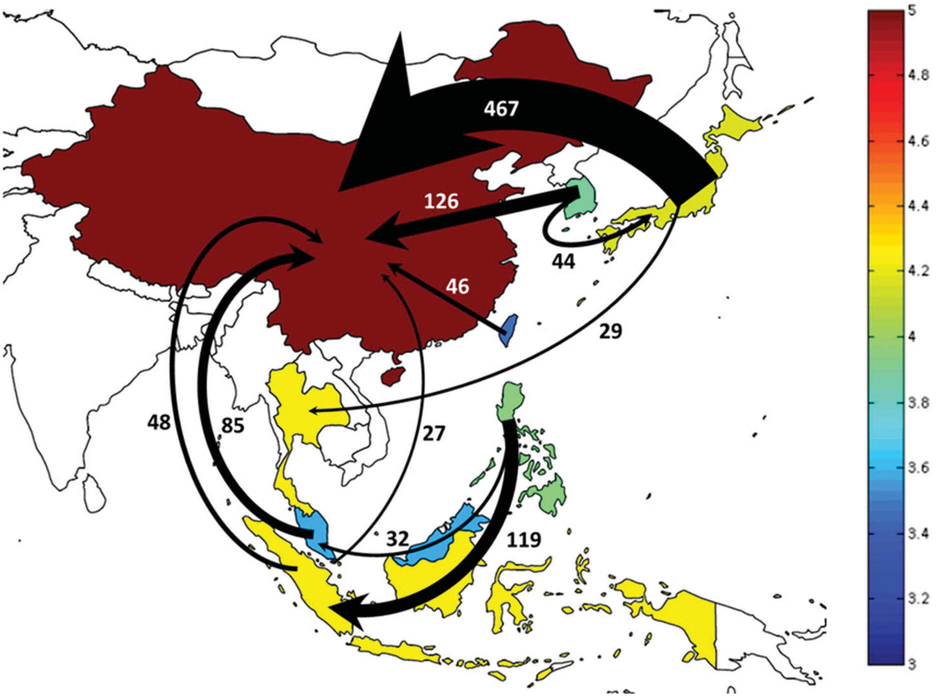
The complexity in atmospheric transport leads to a difference in spatial distribution between $PM_{2.5}$ emissions and health impacts associated with them. We note a few particular cases where this disconnect has an effect: just 4% of Indonesian-consumption-induced emissions occur abroad, yet 28% of the associated mortality occurs abroad. Similarly for Malaysia, 32% of consumption-induced emissions occur abroad, whereas 92% of the associated mortality occurs abroad.

4.2. *Key sectors*

Although the results of consumption-based emissions and health impacts described in the previous section are important for understanding how a specific country contributes to the emissions and impacts in that and other countries, those results do not provide any policy guidance for mitigating air pollutions. It would be useful for policy-makers in a specific Asian country and/or the Southeast Asian community (i.e. Association of South–East Asian Nations (ASEAN)) to identify high-priority industrial sectors and critical supply chains in terms of influence on the air pollution in Asia.

We identified high-priority sectors with high power of dispersion and high sensitivity of dispersion using the key sector analysis described in the Methods section. A high power of dispersion indicates that an increase in the final demand of a specific sector has considerable health impacts throughout the 'upstream' productions in Asian supply chains. On the other hand, a high sensitivity of dispersion in a sector indicates that increased final demand of all other sectors has considerable health impacts throughout the production of that sector. Table 1 shows the top 10 sectors ranked by power of dispersion for 2005. This

Figure 4. $PM_{2.5}$ emissions of each country triggered by final demand of the Asian nine countries and the United States and net health impact transfers (i.e. premature mortality in persons) arising from the consumption-based emissions.



Note: The background color shows the common logarithms of the consumption-based emissions and the arrows indicate top 10 net health impact transfers from consumption-based emissions.

Table 1. Top 10 sectors ranked in terms of power of dispersion (backward linkages effect) in consumption-based health impacts in 2005.

Unweighted index of power of dispersion				Weighted index of power of dispersion			
Rank	$\widetilde{PD}_j^s$	Country	Industry	Rank	$\widetilde{PD}_j^{s*}$	Country	Industry
1	129.46	Thailand	Other grain	1	125.22	China	Building construction
2	65.61	Japan	Iron ore	2	53.01	China	Other grain
3	43.21	China	Other grain	3	43.69	China	Livestock and poultry
4	24.79	Thailand	Food crops	4	36.32	China	Food crops
5	21.01	Japan	Other metallic ore	5	33.03	China	Other food products
6	14.32	Malaysia	Food crops	6	24.33	China	Transportation
7	13.56	China	Paddy	7	24.06	China	Other construction
8	12.28	Philippines	Food crops	8	23.03	China	Public administration
9	9.53	China	Food crops	9	22.16	China	Other service
10	7.62	Malaysia	Paddy	10	21.13	China	Education and research

table highlights that the Asian health impacts tend to increase due to increases in the final demand of 'Other grain of Thailand ($\widetilde{PD}_j^s$: 129.46)', 'Iron ore of Japan ($\widetilde{PD}_j^s$: 65.61)', 'Other grain of China ($\widetilde{PD}_j^s$: 43.21)', 'Food crops of Thailand ($\widetilde{PD}_j^s$: 24.79)', and 'Other metallic ore of Japan ($\widetilde{PD}_j^s$: 21.01)' (see the unweighted index of power of dispersion in Table 1 and/or Figure 5). An important finding is that if we consider the relative importance of

Figure 5. Relationship between power of dispersion and sensitivity of dispersion in health impacts arising from $PM_{2.5}$ emissions.

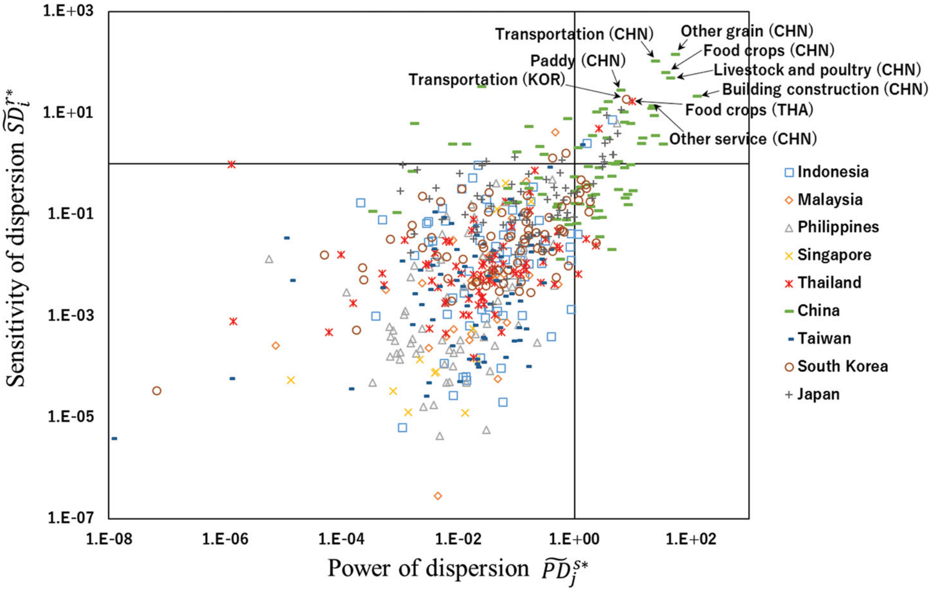


Table 2. Top 10 sectors ranked in terms of sensitivity of dispersion (forward linkages effect) in consumption-based health impacts in 2005.

Unweighted index of sensitivity of dispersion				Weighted index of sensitivity of dispersion			
Rank	$\widetilde{SD}_j^s$	Country	Industry	Rank	$\widetilde{SD}_j^{s*}$	Country	Industry
1	129.59	Thailand	Other grain	1	144.89	China	Other grain
2	79.25	China	Other grain	2	109.50	China	Transportation
3	65.47	Japan	Iron ore	3	64.76	China	Food crops
4	46.60	China	Transportation	4	50.32	China	Livestock and poultry
5	44.49	Thailand	Food crops	5	33.93	China	Iron and steel
6	33.02	Malaysia	Food crops	6	29.05	China	Paddy
7	21.24	Japan	Other metallic ore	7	21.78	China	Building construction
8	20.15	China	Food crops	8	19.15	Korea	Transportation
9	19.86	Korea	Transportation	9	17.18	China	Other non-metallic mineral products
10	19.32	China	Paddy	10	16.97	Thailand	Food crops

sectoral final demand, the Chinese sectors such as Building construction and Other grain are ranked among the top 10 sectors (see the weighted index of power of dispersion in Table 1). Consequently, these high-ranking sectors can be considered the environmentally important sectors which strongly affect the air pollution through the Asian supply chains. It should be noted that the positions of the high-ranking sectors in terms of sensitivity of dispersion do not change considerably (Table 2 and/or Figure 5). For the weighted index of sensitivity of dispersion, 'Transportation of South Korea' is among the top 10 sectors (Table 2).

Any pollution abatement measures employed in these key sectors showing high indices of power of dispersion and sensitivity of dispersion, especially Building construction of China, Other grain of China, and Livestock and poultry of China, are crucial in reducing health impacts arising from the $PM_{2.5}$ emissions throughout the entire economy. For the top-ranked key sectors, it is crucial to monitor the impact of technological changes and support alternative technologies that use less pollution-intensive materials and achieve higher energy efficiencies.

4.3. Critical supply chain paths

Although the key sector analysis is useful for identifying the high-priority sectors that have contributed to the health impacts in Asia and for formulating an effective mitigation policy aimed at the identified sector, this analysis method was unable to determine which supply chain paths in complex production networks make the greatest contribution to the increase in premature deaths due to air pollution. In this section, we therefore employed SPA to try to break down these consumption-based health impacts for different supply chain paths, extending from final demand to producers and including cross-border pollution. We go on to discuss an additional mitigation policy from the point of view of supply chain engagement.

Table 3 shows the top 30 supply chain paths ranked by the health impacts among the Asian supply chains. The path ranked as No. 1 here, CHN → CHN.2 → CHN, shows that $PM_{2.5}$ emitted from a given industry sector originating from final demand in China (driver country) for China's 'Other grain' (No. 2) sector has health impacts

Table 3. Top 30 supply chain paths ranked in terms of health impacts in Asia.

Rank	Premature deaths (persons)	Driver country		Path		Receptor country
1	1530	CHN	→	CHN.2	→	CHN
2	875	CHN	→	CHN.3	→	CHN
3	730	CHN	→	CHN.5	→	CHN
4	693	CHN	→	CHN.63 → CHN.2	→	CHN
5	619	CHN	→	CHN.63	→	CHN
6	473	CHN	→	CHN.66	→	CHN
7	351	CHN	→	CHN.70	→	CHN
8	276	CHN	→	CHN.75	→	CHN
9	264	CHN	→	CHN.63 → CHN.66	→	CHN
10	259	THA	→	THA.3	→	THA
11	211	CHN	→	CHN.63 → CHN.40	→	CHN
12	207	CHN	→	CHN.63 → CHN.3	→	CHN
13	173	CHN	→	CHN.74	→	CHN
14	160	CHN	→	CHN.1	→	CHN
15	159	CHN	→	CHN.69	→	CHN
16	155	CHN	→	CHN.5 → CHN.2	→	CHN
17	147	CHN	→	CHN.15 → CHN.3	→	CHN
18	139	CHN	→	CHN.63 → CHN.38	→	CHN
19	138	CHN	→	CHN.63 → CHN.1	→	CHN
20	135	JPN	→	JPN.66	→	JPN
21	133	CHN	→	CHN.7	→	CHN
22	132	CHN	→	CHN.64 → CHN.2	→	CHN
23	122	KOR	→	KOR.66	→	KOR
24	117	CHN	→	CHN.12 → CHN.2	→	CHN
25	116	CHN	→	CHN.66 → CHN.41	→	CHN
26	104	CHN	→	CHN.15 → CHN.2	→	CHN
27	102	CHN	→	CHN.15 → CHN.1	→	CHN
28	102	PHL	→	PHL.3	→	IDN
29	101	CHN	→	CHN.64	→	CHN
30	97	IDN	→	IDN.2	→	IDN

on China (receptor country). The $PM_{2.5}$ emissions and pollution (within China) generated throughout this supply chain path induced 1530 premature deaths within China. The health impacts of $PM_{2.5}$ generated as a result of final demand for pollution-intensive agricultural industry sectors such as ‘Paddy’ (No. 1), ‘Other grain’ (No. 2), ‘Food crops’ (No. 3), and ‘Livestock and poultry’ (No. 5) are striking. Other high-ranking paths shown in Table 3 that are centered on agricultural activities are CHN → CHN.15 → CHN.3 → CHN, CHN → CHN.12 → CHN.2 → CHN, and CHN → CHN.15 → CHN.2 → CHN, revealing that direct and indirect $PM_{2.5}$ emissions from the production of agricultural products that serve as inputs for the production of ‘Milled grain and flour’ (No. 12) and ‘Other food products’ (No. 15) also exert a large influence on health.

Direct emissions arising from final demand for China’s ‘Building construction’ (No. 63) sector also account for a large number of premature deaths (Table S1). Interestingly, the fact that the paths CHN → CHN.63 → CHN.2 → CHN, CHN → CHN.63 → CHN.3 → CHN, and CHN → CHN.64 → CHN.2 → CHN are all ranked highly in Table 3 shows that transactions between construction sectors (e.g. ‘Building construction’, No. 63 and ‘Other construction’, No. 64) and agricultural sectors (e.g. ‘Paddy’, ‘Other grain’, and ‘Food crops’) are comparatively pollution intensive. In addition to agriculture-related activities, we can note that construction gives rise to substantial $PM_{2.5}$ emissions in the

Table 4. Top 30 supply chain paths ranked in terms of health impacts in other countries due to emissions attributable to final demand of a specific driver country.

Rank	Premature deaths (persons)	Driver country		Path		Receptor country
1	102	PHL	→	PHL.3	→	IDN
2	48	USA	→	CHN.66	→	CHN
3	30	PHL	→	PHL.3	→	MYS
4	27	KOR	→	KOR.15 → CHN.3	→	CHN
5	25	KOR	→	KOR.66	→	CHN
6	25	JPN	→	CHN.66	→	CHN
7	19	KOR	→	KOR.66	→	JPN
8	17	CHN	→	KOR.66	→	KOR
9	16	JPN	→	CHN.74	→	CHN
10	13	KOR	→	KOR.12 → CHN.12	→	CHN
11	12	USA	→	KOR.66	→	KOR
12	12	TWN	→	TWN.66	→	CHN
13	12	CHN	→	CHN.2	→	JPN
14	10	USA	→	CHN.60 → CHN.5	→	CHN
15	10	THA	→	THA.3	→	IDN
16	9	THA	→	THA.3	→	TWN
17	9	THA	→	THA.3	→	PHL
18	8	MYS	→	MYS.3	→	CHN
19	8	IDN	→	IDN.3	→	MYS
20	8	THA	→	THA.66	→	CHN
21	8	USA	→	CHN.19 → CHN.2	→	CHN
22	7	CHN	→	CHN.2	→	KOR
23	7	USA	→	CHN.65	→	CHN
24	7	USA	→	JPN.66	→	JPN
25	7	CHN	→	CHN.3	→	JPN
26	7	JPN	→	JPN.15 → CHN.2	→	CHN
27	7	JPN	→	JPN.66	→	CHN
28	7	IDN	→	IDN.3	→	TWN
29	6	USA	→	CHN.23 → CHN.5	→	CHN
30	6	USA	→	CHN.66 → CHN.66	→	CHN

'Transportation' (No. 66) sector; these emissions have large health impacts on people within China. From this, we see that as capital formation continues in China, the adverse health impacts of direct and indirect $PM_{2.5}$ emissions and other forms of air pollution from pollution-intensive transport and agriculture-related activities are likely to increase.

Table 4 shows the top 30 supply chain paths that have relatively large health impacts on Asian countries other than the driver country as a result of final demand in a specific driver country. The path having the greatest impact is PHL → PHL.3 → IDN, and we can note that the contribution of final demand in Philippines on food crops in Philippines accounts for 102 premature deaths in Indonesia. As shown for the paths ranked Nos. 1 and 3 in Table 4, direct and indirect $PM_{2.5}$ emissions resulting from the 'Food crops' (No. 3) sectors in Philippines in particular are widely dispersed, as far as Indonesia and Malaysia, to cause crucial health problems in these countries.

In addition, the relationship shown in the 2nd-ranked path in Table 4, USA → CHN.66 → CHN, indicates that $PM_{2.5}$ emissions from transportation in China due to final demand in the United States have health impacts on people in China, by way of territorial air pollution.

As shown in the 13th-ranked path, CHN → CHN.2 → JPN, while the influence of final demand in China on China's agricultural and transportation sectors has an impact on the health of people within China (Table 3), it also contributes to an increase in premature deaths in neighboring countries such as Japan, as a result of cross-border pollution.

From Table 4, of these top 30 paths, 22 start with final demand in one of the other 8 geographically close Asian countries, whereas the remaining 8 paths (30%) start with final demand in the geographically very distant United States, demonstrating that the United States is a major driver country for air pollution in China (Table 4). More specifically, we can say that much of the air pollution in China is driven by the purchase by Americans of Chinese-made industrial products such as those in the 'Other manufacturing products' (No. 60) sectors, as well as those in the 'Weaving and dyeing' (No. 19) and 'Leather and leather products' (No. 23) sectors.

As exemplified by the paths JPN → CHN.66 → CHN and KOR → KOR.15 → CHN.3 → CHN, some supply chain paths give rise to pollution within China by $PM_{2.5}$ emissions generated within China due to direct and indirect demand for industrial activity in China, whereas other supply chain paths, such as KOR → KOR.66 → CHN, result in cross-border pollution through $PM_{2.5}$ emissions generated in other countries (South Korea in this case). From Table 4, we see that the health impacts on China of cross-border pollution occur most notably as a result of emissions from industrial activity in neighboring countries such as Japan, South Korea, Taiwan, and Thailand (in particular from transportation).

4.4. Direct $PM_{2.5}$ emissions from the household sector of countries

For the direct emissions from the household sector of countries g^{s^*}, China is the largest emitter among the nine Asian countries examined, accounting for about four times the consumption-based emissions of China, an amount equivalent to 3.75 million tonnes in 2005 (Table S15). A detailed look at the source of emissions shows that 0.86 million tonnes of these emissions are generated by industries in China to meet final demand of China, whereas 3.75 million tonnes are direct emissions by the household sector. The number of premature deaths in China triggered by the direct emissions from the household sector of China is much more important than that that of those triggered by the industrial emissions associated with final demand of China. Thus, energy consumption by the household sector (e.g. by the burning of biomass) has a much greater impact on air pollution than energy consumption by industry. As in previous studies (Yan et al., 2011; Shan et al., 2015), in developing measures to combat air pollution in China and the whole of East Asia, the higher priority should be cutting pollution from China's household sector, by reducing reliance on carbon-based fuels for heating equipment.

4.5. Comparison between this study and Anenberg et al. (2011)

A seminal article by Anenberg et al. (2011) reported that the total of territorial BC emissions (industrial BC emissions plus residential BC emissions) in five East Asian countries (China, Japan, South Korea, North Korea, and Mongolia) was 1800 Gg-C in 2000 (Figure 1 in Anenberg et al., 2011), whereas the BC emission inventory database used in the present study (Takahashi et al., 2014) shows that the total of territorial BC emissions in only three of these East Asian countries (China, Japan, and South Korea) was 1419 Gg-C in 2005 (Figure S2). Although study year and country coverage differ between the two studies, we can see that the annual BC emissions in East Asia constituted more than 1400 Gg-C during 2000–2005.

Anenberg et al. (2011) also found that the number of avoidable premature deaths per unit of territorial BC emissions was 80 persons/Gg-C in 5 East Asian countries, whereas our consumption-based accounting analysis shows that the number of avoidable premature deaths per unit of consumption-based BC emissions was 25 persons/Gg-C in 3 East Asian countries, which is considerably less. We see that this difference in health impact is caused by the parameter settings in the atmospheric simulation models employed in Anenberg et al. (2011) and Takahashi et al. (2014). Anenberg et al. (2011) used the MOZART-4 simulation model configured with a horizontal grid resolution of 200 kilometer and daily concentration estimates, whereas Takahashi et al. (2014) used the CMAQ modeling system (Byun and Schere, 2006) configured with a horizontal grid resolution of 80 kilometer and seasonal concentration estimates. It is very difficult to examine the differences between these model-oriented results and such a sensitivity analysis over simulation models and a wide range of parameter settings is beyond the scope of the present paper, but remains as important future work. The absolute magnitude of health impacts is uncertain due to simulation settings, but it is nevertheless important to note that the present study could identify environmentally important supply chain paths and key sectors that have made relatively large contributions to air pollution in East Asian countries.

5. Discussion and conclusion

The results of this study revealed that the supply chain paths with the greatest impact on human health in the Asia region are centered around agricultural activities in China (involving for example, the key sectors of 'Paddy', 'Other grain', and 'Food crops') and construction activities in China. The main cause of emissions from China's agricultural sector is the incineration of straw, stalks, and other crop residues after harvest. The incineration of rice straw and wheat straw in rural areas makes a particularly large contribution to pollution. Thus, the most important approach to cutting $PM_{2.5}$ emissions across the whole of Asia is for the Chinese government to implement policies and regulations in rural China that promote the recycling of straw, stalks, and other crop residues (e.g. by converting them to livestock feed or bioethanol) and prevent or limit the incineration of such waste. Not only in China but in Thailand and Malaysia, identified as key sectors in Tables 1 and 2, the highest priority mitigation policy is to aid in the change from pollution-intensive agriculture technologies in other grain and food crops to more environmentally friendly technologies. The related technological improvements would contribute to reducing $PM_{2.5}$ emissions through the entire global supply chains.

The transportation sector, which serves to move products across supply chain networks, also plays a major role in air pollution, as a hub of supply chain paths that generate relatively large quantities of $PM_{2.5}$ emissions (Table 3). Of the nine Asian countries analyzed, the transportation sectors of Thailand and China both have relatively high values of $PM_{2.5}$ emissions per unit of output (i.e. are emissions intensive), with values of 1.2 and 0.6 tonnes/million USD, respectively. The corresponding value for Japan is a low 0.06 tonnes/million USD, which means that China's transportation sector is about 10 times more emissions intensive than that of Japan. This wide disparity can be explained by the fact that, whereas Japan's cars, trucks, and other motor vehicles are technically advanced and fuel-efficient, in line with the country's highly developed economy, huge numbers of energy-inefficient, emissions-intensive motor vehicles continue to be used for transportation on China's roadways. In countries like China and Thailand, an effective policy can be a vehicle replacement scheme, replacing older cars that have lower fuel efficiency with greener cars that have higher fuel efficiency, that has been introduced in many developed countries (Kagawa et al., 2013). The results regarding the transportation section also suggest that an important goal for cutting emissions of air pollutants across Asia is to reduce emissions across all of East Asia's supply chains through the adoption of highly efficient transportation technologies like those of Japan, most urgently in China and Thailand.

Figures 2 and 4 clearly show that Japan has triggered $PM_{2.5}$ emissions and $PM_{2.5}$-induced human health impacts in Asia through the supply chain network. We conclude that the Japanese government should positively support Asian countries in changing key high-priority technologies and critical supply chain paths into greener ones.

Lastly, as mentioned in Section 4.4, as its highest priority, the Chinese government should implement a more aggressive policy to cut pollution from China's household sector by replacing carbon-based fuels with environmentally friendly heating equipment.

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