

1   **Quantifying the mutual contributions of PM<sub>2.5</sub> pollution and associated population exposure  
2   and premature deaths among China, South Korea, and Japan: A dual perspective and an  
3   interdisciplinary approach**

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16   **Author Contribution**

17   JL and FY contributed equally to this work. JL conceived the project. JL and HC prepared the  
18   emission inventory with contributions from FY. FY performed and evaluated GEOS-Chem model  
19   simulations with contributions from JL. JL performed the calculations of population-weighted  
20   mean PM<sub>2.5</sub> concentrations, PM<sub>2.5</sub> population exposure, and PM<sub>2.5</sub>-related premature deaths with  
21   contributions from HZ. JL and FY analysed and interpreted the results. JL and FY wrote the  
22   manuscript with contributions from HC and HZ. HZ reviewed the manuscript. All authors  
23   contributed to the development of the manuscript and approved the final version for publication.  
24   JL and FY have verified the underlying data and have full access to all the data in the study.

25   **Declaration of conflicts of interest**

26   The authors declare no competing financial interests.

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32 **Abstract**

33 **Background:**

34 Transboundary PM<sub>2.5</sub> pollution in Northeast Asia is causing significant environmental conflicts  
35 among China, South Korea, and Japan. However, efforts to address these conflicts have been  
36 impeded by a lack of a comprehensive understanding of source-receptor relationship of PM<sub>2.5</sub>  
37 pollution and associated health impacts among these countries.

38 **Objectives:**

39 We quantify the extent to which transboundary PM<sub>2.5</sub> pollution and associated health impacts are  
40 mutual among the three countries in 2015 and 2017 using three metrics (population-weighted mean  
41 PM<sub>2.5</sub> concentration, PM<sub>2.5</sub> population exposure, and PM<sub>2.5</sub>-related premature deaths) and two  
42 accounting perspectives (production and consumption).

43 **Methods:**

44 We adopt an integrated interdisciplinary analysis framework that links a multi-regional input-  
45 output model, a GEOS-Chem chemical transport model, a population exposure model, and an  
46 exposure-response model.

47 **Results:**

48 From a production perspective, China's contributions to population-weighted mean PM<sub>2.5</sub>  
49 concentrations in South Korea and Japan are considerable, while the contributions of South Korea  
50 and Japan to China are negligible. However, the contributions from South Korea and Japan to  
51 PM<sub>2.5</sub> population exposure and associated premature deaths in China are nonnegligible from both  
52 production and consumption perspectives. From a consumption perspective, the contributions of  
53 South Korea and Japan to PM<sub>2.5</sub>-related premature deaths in China amount to 6.96 [95%  
54 confidence interval (CI): 6.36, 7.56] and 9.79 (95% CI: 8.93, 10.64) thousand deaths in 2015,  
55 respectively, and 5.03 (95% CI: 4.55, 5.49) and 7.75 (95% CI: 7.02, 8.47) in 2017, respectively.  
56 These figures are larger than China's contributions to PM<sub>2.5</sub>-related premature deaths in South  
57 Korea and Japan, which measure 4.63 (95% CI: 3.97, 5.28) and 3.91 (95% CI: 2.78, 5.01) thousand  
58 deaths in 2015, respectively, and 4.43 (95% CI: 3.75, 5.1) and 3.69 (95% CI: 2.57, 4.79) in 2017,  
59 respectively.

60 **Discussion:**

61 Our findings show that mutual contributions of PM<sub>2.5</sub> pollution and associated health impacts  
62 among the three countries vary considerably when different metrics and accounting perspectives  
63 are applied. A consumption perspective reveals narrower gaps in mutual contributions than a  
64 production perspective. Our findings could help policy makers, scholars, and the general public in  
65 China, South Korea, and Japan understand the intricacies involved in assigning environmental  
66 responsibilities and achieving environmental justice with respect to transboundary PM<sub>2.5</sub> pollution.

67 **Keywords**

68 Transboundary PM<sub>2.5</sub> pollution; Source-receptor relationship; Trade; Premature deaths; PM<sub>2.5</sub>  
69 population exposure; Northeast Asia.

70 **1. Introduction**

71 Transboundary fine particulate matter ( $PM_{2.5}$ ) pollution has become an increasingly significant  
72 and sensitive environmental issue in China, South Korea, and Japan due to its adverse impacts on  
73 human health. This has led to a proliferation of studies focusing on the source–receptor relationship  
74 (SRR) of  $PM_{2.5}$  pollution among these countries in recent years.<sup>1,2</sup> These studies allow for an  
75 understanding of the source areas of transboundary  $PM_{2.5}$  pollution in Northeast Asia (NEA) and  
76 their source contributions to receptor countries via atmospheric transport.<sup>3–7</sup> However, most of  
77 these studies attribute the pollution to a country only by evaluating the direct air pollutant  
78 emissions produced in that country, but overlook the indirect air pollutant emissions embodied in  
79 cross-border trade caused by consumption in other countries. A typical anthropogenic emission  
80 process of air pollutants is not only executed by producers, but also stimulated by consumers,<sup>8</sup>  
81 which raises a critical question about to which extent the consumer countries that have benefited  
82 from the emission process should be accountable for the emission and the consequent air pollution.  
83 Therefore, it is recommended that future studies on the SRR of  $PM_{2.5}$  pollution in NEA should  
84 consider both production and consumption perspectives.<sup>1</sup>

85 A production perspective views all emissions produced in a country as the responsibility of  
86 that country. Clearly, only the impact of atmospheric transport on the air quality in downwind  
87 countries will be considered when examining the SRR of  $PM_{2.5}$  pollution from this perspective.  
88 By contrast, a consumption perspective regards all emissions induced by the consumption of a  
89 country via the trade of goods and services to be the responsibility of that country, irrespective of  
90 the countries where the emissions are produced.<sup>9–12</sup> In this sense, not only atmospheric transport  
91 relocates  $PM_{2.5}$  pollution between countries, but also trade displaces  $PM_{2.5}$  pollution by physically  
92 separating the production and consumption activities. The consumption perspective has been  
93 explored in air pollution studies both internationally<sup>11,13</sup> and nationally<sup>14–16</sup>; however, it has not  
94 been used to examine the SRR of  $PM_{2.5}$  pollution in NEA especially on the country level that is  
95 required to guide local actions. A related study examines the consumption-based health burdens  
96 of black and organic carbon in Asia,<sup>17</sup> but it neither investigates the lumped  $PM_{2.5}$ , nor provides a  
97 production-based analysis of concentrations of black and organic carbon or the associated health  
98 impacts. Therefore, the SRR of  $PM_{2.5}$  pollution in NEA from a consumption perspective and their  
99 differences from those of a production perspective remain unknown.

100 Here, we adopt an integrated analysis framework, consisting of a multi-regional input-output  
101 (MRIO) model, a GEOS-Chem chemical transport model, a population exposure model, and an  
102 exposure-response model, to provide a contemporary, comprehensive, and quantitative analysis of  
103 the SRR of  $PM_{2.5}$  pollution and associated health impacts among China, South Korea, and Japan  
104 in 2015 and 2017. For modelling purposes, we use the latest detailed sectoral emission dataset, the  
105 Emissions Database for Global Atmospheric Research v6.1 (EDGARv6.1).<sup>18</sup> EDGARv6.1  
106 incorporates China's substantial emission reductions since 2013 due to its five-year clean air  
107 actions.<sup>19</sup> This allows us to capture possible changes over time in China's contributions to  $PM_{2.5}$   
108 pollution and associated health impacts in South Korea and Japan, which was not possible in prior  
109 studies due to data unavailability.<sup>13,17</sup> Our experimental design enables us to quantify the extent to  
110 which transboundary  $PM_{2.5}$  pollution and associated health impacts are mutual among nations in  
111 NEA.

112 **2. Methods**

113 We adopt an integrated analysis framework that consists of four steps (Figure S1). First, we use a  
114 MRIO model to develop the consumption-based emission inventories based on China's MRIO  
115 tables<sup>20</sup>, the Organization for Economic Cooperation and Development (OECD) inter-country

116 input–output (ICIO) tables,<sup>21</sup> and the production-based emission inventory EDGARv6.1.<sup>18</sup>  
 117 Second, we use the GEOS-Chem chemical transport model to simulate the surface PM<sub>2.5</sub>  
 118 concentrations in China, South Korea, and Japan under a baseline and nine emission-reduction  
 119 scenarios (Table 1). The simulation results of the nine emission-reduction scenarios are compared  
 120 with that of the baseline scenario to determine the grid-level fractional contributions to PM<sub>2.5</sub>  
 121 pollution from production- and consumption-based emissions in NEA countries. In the third and  
 122 fourth steps, we use the fractional contributions, satellite-based PM<sub>2.5</sub> data, and other auxiliary data  
 123 in an exposure model and an exposure-response model to calculate the population-weighted mean  
 124 (PWM) PM<sub>2.5</sub> concentrations, PM<sub>2.5</sub> population exposure, PM<sub>2.5</sub>-related premature deaths, and  
 125 contributions from source countries to these metrics in receptor countries. Additional details on  
 126 each step are as follows.

## 127 **2.1. Multi-regional input-output model for deriving consumption-based emissions**

128 We calculate the consumption-based emissions via an input–output analysis of the economic  
 129 output in monetary unit required to produce goods and services for consumption in a region,  
 130 multiplied by emission intensities. We perform the input-output analysis on a sector and region  
 131 basis using a MRIO model that combines China's MRIO tables obtained from the Carbon  
 132 Emission Accounts & Datasets with the OECD ICIO tables.<sup>21</sup> The MRIO model describes the  
 133 transactions of products within and among China, South Korea, Japan, and other regions. By  
 134 capturing the economic processes among sectors and regions, the model enables the tracing of the  
 135 consumption in a region to its source region of production.<sup>9</sup>

136 The MRIO model consists of 95 regions, including 31 provinces of mainland China and 64  
 137 OECD countries/regions including South Korea and Japan (Table S1). The MRIO model begins  
 138 with the following equation for monetary flows:

$$139 \begin{pmatrix} x_1 \\ x_r \\ \vdots \\ x_{95} \end{pmatrix} = \begin{pmatrix} A_{1,1} & \dots & A_{1,s} & \dots & A_{1,95} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ A_{r,1} & \dots & A_{r,s} & \dots & A_{r,95} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ A_{95,1} & A_{95,s} & \dots & A_{95,95} \end{pmatrix} \begin{pmatrix} x_1 \\ x_r \\ \vdots \\ x_{95} \end{pmatrix} + \begin{pmatrix} \Sigma_s \Sigma_t y_{1,s}^t \\ \vdots \\ \Sigma_s \Sigma_t y_{r,s}^t \\ \vdots \\ \Sigma_s \Sigma_t y_{95,s}^t \end{pmatrix} \quad [1]$$

140 where  $x_r$  ( $r = 1, 2, \dots, 95$ ) is a vector of the total economic output for each sector in region  $r$ . The  
 141 subscripts ranging from 1 to 31 indicate the 31 provinces of mainland China, and the subscripts  
 142 ranging from 32 to 95 indicate the 64 OECD countries/regions.  $A_{r,s}$  ( $r = 1, 2, \dots, 95, s = 1, 2, \dots,$   
 143 95) represents the matrix of direct consumption coefficients in which the columns represent the  
 144 amount of input from the sectors in region  $r$  required for one unit of output to be produced by each  
 145 sector in region  $s$ .  $y_{r,s}^t$  is the final demand in region  $s$ , which is satisfied by the goods produced  
 146 in region  $r$ .  $t$  refers to different types of final demand, including consumption by rural and urban  
 147 residents, government investment, fixed asset investment, and others. A simplified version of  
 148 Equation [1] is as follows:

$$149 \quad \mathbf{x} = A\mathbf{x} + \mathbf{y} \quad [2]$$

150 where  $\mathbf{x}$  is the matrix of the total economic output,  $A$  is the matrix of direct consumption  
 151 coefficients, and  $\mathbf{y}$  is the matrix of final demand.

152 If Equation [2] is solved for the total economic output, then it can be expressed as:

153  $\mathbf{x} = (I - A)^{-1}\mathbf{y}$  [3]

154 where  $I$  is the identity matrix and  $(I - A)^{-1}$  denotes the Leontief inverse matrix. By  
155 multiplying the economic output with the emission intensity, the emissions produced in one region  
156 for consumption in a different region can be calculated as:

157  $\mathbf{E} = \hat{f}(I - A)^{-1}\mathbf{y}$  [4]

158 where  $\mathbf{E}$  represents the emissions of air pollutants induced by consumption,  $\hat{f}$  is a diagonal  
159 matrix of the region- and sector-specific emission intensities (pollutant emissions per unit of  
160 economic output).

161 To facilitate the MRIO analysis, we combine and match the sectors in the China's MRIO  
162 tables, OECD ICIO tables, and EDGARv6.1 dataset through a mapping process (Tables S2, S3,  
163 and S4) adapted from previous consumption-based studies.<sup>15</sup> In addition, we assume that the  
164 consumption-based emission inventory has the same spatial distribution as the production-based  
165 emission inventory for each sector. Therefore, we use the latter as the spatial proxy to distribute  
166 the former from regional to grid level to facilitate the GEOS-Chem chemical transport model  
167 simulations.

## 168 2.2. GEOS-Chem chemical transport model for simulating PM<sub>2.5</sub> concentrations

169 We run v12.9.3 of GEOS-Chem tropospheric chemistry (“tropchem”) mechanism to provide  
170 surface PM<sub>2.5</sub> concentrations at a horizontal resolution of 0.5° latitude and 0.625° longitude for  
171 the months of January through December in 2015 and 2017 within a self-defined study domain  
172 (Figure S2). The study domain covers China, South Korea, and Japan, as well as potential source  
173 areas of PM<sub>2.5</sub> pollution in Northeast Asia (NEA) such as South and Central Asia. We perform two  
174 self-consistent global runs using GEOS-Chem to provide initial and time-dependent lateral  
175 boundary conditions at a horizontal resolution of 2° latitude and 2.5° longitude that are necessary  
176 for regional runs. These two global runs cover the periods of July 2014 to December 2015 for the  
177 2015 simulation and July 2016 to December 2017 for the 2017 simulation. The first six months of  
178 each run serve as the model spin-up. Both global and regional runs are driven by the meteorology  
179 from the Modern-Era Retrospective analysis for Research and Applications version 2 (MERRA-  
180 2).<sup>22</sup> We employ EDGARv6.1 anthropogenic emissions and other GEOS-Chem default emissions  
181 (Table S5). We turn off emissions in the latter that exist in the former, which include emissions  
182 from anthropogenic activities, agricultural soil nitrogen oxides (NOx), agricultural waste burning,  
183 aviation, and shipping, to avoid double counting. In practice, we initially have an insufficiently  
184 high model performance for black carbon. We improve its simulation by re-distributing its  
185 emissions in EDGARv6.1 to the spatial profile of black carbon emissions in MIX Asian emission  
186 inventory<sup>23</sup> that can better represent regional characteristics.

187 We evaluate the model performance using hourly PM<sub>2.5</sub> concentration measurements  
188 collected from 1) China National Environmental Monitoring Center (CNEMC); 2) AirKorea of  
189 the Korean Ministry of Environment; 3) Atmospheric Environmental Regional Observation  
190 System (AEROS), the Ministry of the Environment Government of Japan; and 4) Acid Deposition  
191 Monitoring Network in East Asia (EANET). In addition, we evaluate the model performance using  
192 ground measurements of PM<sub>2.5</sub> chemical components (sulfate, nitrate, ammonium, organic carbon  
193 (OC), and black carbon (BC)) collected from a variety of sources.<sup>24</sup>

194 To ensure the accuracy of the evaluation of the model performance, we perform a  
195 comprehensive data quality check of the hourly PM<sub>2.5</sub> concentration measurements. This involves  
196 removing any problematic data points using data quality control procedures that have been  
197 established in previous studies<sup>25,26</sup>:

- 198 1. Convert the timestamps of all hourly observation data to the Universal Coordinated Time  
199 (UTC).

200 The air quality monitoring systems in different countries record hourly observation data using  
201 different time zone settings. For example, CNEMC records hourly PM<sub>2.5</sub> concentration  
202 measurements using China Standard Time (UTC+8:00), while AirKorea and AEROS use  
203 Korean Standard Time and Japan Standard Time (UTC+9:00), respectively. To facilitate the  
204 comparison between observed and modelled data, we convert the timestamps of all hourly  
205 observation data to UTC.

- 206 2. Set lower and upper limits of hourly PM<sub>2.5</sub> concentration measurements to [0, 3000] µg/m<sup>3</sup>.

207 We consider hourly PM<sub>2.5</sub> concentration measurements less than 0 µg/m<sup>3</sup> or exceeding 3000  
208 µg/m<sup>3</sup> as potential instrumental failures and therefore remove them from further analysis by  
209 setting their values to NaN (Not a Number).

- 210 3. Remove PM<sub>2.5</sub> concentration measurements that exceed concurrently co-located PM<sub>10</sub>  
211 concentration measurements.

212 PM<sub>2.5</sub> concentration measurements are the mass of particles with an aerodynamic diameter less  
213 than 2.5 µm per unit volume of air, while PM<sub>10</sub> concentration measurements are the mass of  
214 particles with an aerodynamic diameter less than 10 µm per unit volume of air. It is clear that  
215 at any given time and location, the PM<sub>2.5</sub> concentration measurements should never exceed  
216 those of PM<sub>10</sub>.<sup>25</sup> Therefore, we consider PM<sub>2.5</sub> concentration measurements that exceed  
217 concurrently co-located PM<sub>10</sub> concentration measurements as problematic measurements, and  
218 subsequently remove them from further analysis by setting their values to NaN.

- 219 4. Eliminate any series of five consecutive hourly PM<sub>2.5</sub> concentration measurements that are  
220 identical in value.

221 PM<sub>2.5</sub> measurements are typically volatile, so it is highly unlikely for air quality monitoring  
222 instrument to record the same value for five consecutive hours.<sup>25</sup> As a result, we consider any  
223 such repeated measurements to be potential instrumental errors and mark them as invalid by  
224 setting their values to NaN.

- 225 5. Remove any extreme jumps in hourly PM<sub>2.5</sub> concentration measurements.

226 Occasionally, meteorological events such as strong winds can cause dramatic changes in PM<sub>2.5</sub>  
227 concentration measurements. However, these events are usually accompanied by sustained  
228 high PM<sub>2.5</sub> concentrations either before or after their occurrence. As a result, it is unlikely for  
229 PM<sub>2.5</sub> concentrations to change abruptly without any connection to the measurements before  
230 or after.<sup>26</sup> To identify problematic abrupt changes in PM<sub>2.5</sub> concentration measurements, we  
231 adopt the method proposed by Jiang, Jolleys<sup>26</sup>. This involves two steps: first, if the hourly  
232 change in PM<sub>2.5</sub> concentration at a given hour (t), relative to t-1 and t+1, is greater than 15  
233 times the hourly change in PM<sub>2.5</sub> concentration at t-1 relative to t-2, and greater than 15 times  
234 the hourly change in PM<sub>2.5</sub> concentration at t+1 relative to t+2, then the PM<sub>2.5</sub> concentration at  
235 t is considered invalid and set to NaN. Second, if the hourly change in PM<sub>2.5</sub> concentration at

236 a given hour (t) relative to t-1 is greater 20 times the hourly change in PM<sub>2.5</sub> concentration at  
237 t-1 relative to t-2, and the PM<sub>2.5</sub> concentration at t+1 is invalid, then the PM<sub>2.5</sub> concentration at  
238 t is considered invalid and set to NaN.

- 239 6. Check the continuity of hourly PM<sub>2.5</sub> concentration measurements at each air quality  
240 monitoring site.

241 If more than 10% of the hourly measurements at an air quality monitoring site in a given year  
242 are missing or marked as invalid after applying the quality control steps described above, we  
243 remove that site's data from our analysis for that year.

244 After performing the data quality check, we compare *in situ* observations and model  
245 simulations of lumped PM<sub>2.5</sub> on a yearly scale. For PM<sub>2.5</sub> chemical components (sulfate, nitrate,  
246 ammonium, OC, and BC), we compile the modelled values according to the monitoring period for  
247 each observation of PM<sub>2.5</sub> chemical components, as the monitoring periods for observation data of  
248 PM<sub>2.5</sub> chemical components can vary from several days to months.<sup>24</sup>

249 To describe the comparisons between *in situ* observations and model simulations, we use the  
250 Pearson correlation coefficients (R), normalized mean bias (NMB), normalized mean error  
251 (NME), mean fractional bias (MFB), and mean fractional error (MFE)<sup>27</sup>:

252 
$$R = \frac{\sum_1^N (M - \bar{M})(O - \bar{O})}{\sqrt{\sum_1^N (M - \bar{M})^2 \sum_1^N (O - \bar{O})^2}} \quad [5]$$

253 
$$NMB = \frac{\sum_1^N (M - O)}{\sum_1^N O} \quad [6]$$

254 
$$NME = \frac{\sum_1^N |M - O|}{\sum_1^N O} \quad [7]$$

255 
$$MFB = \frac{1}{N} \sum_1^N \left( \frac{M - O}{O + M / 2} \right) \quad [8]$$

256 
$$MFE = \frac{1}{N} \sum_1^N \left| \frac{M - O}{O + M / 2} \right| \quad [9]$$

257 Where M and O refer to modelled and observed values, respectively;  $\bar{M}$  and  $\bar{O}$  are the respective  
258 means of M and O, and N denotes the number of comparison points.

259 Table S6 shows the evaluation of concentrations of simulated PM<sub>2.5</sub> and its chemical  
260 components against ground measurements data. For the lumped PM<sub>2.5</sub>, the Pearson correlation  
261 coefficients, NMB, NME, MFB and MFE between modelled and observed values for the years of  
262 2015 and 2017 are 0.71 and 0.75, 39.0% and 39.9%, 49.0% and 49.4%, 20.2% and 21.9%, 28.7%  
263 and 29.1%, respectively. For model evalution of concentrations of PM<sub>2.5</sub> chemical components in  
264 2015, the Pearson correlation coefficients, NMB, NME, MFB and MFE between modelled and  
265 observed values range from 0.48 to 0.69, -12.7% to 34.6%, 30.5% to 58.8%, -1.2% to 29.1%,  
266 23.9% to 44.2%, respectively. For model evalution of concentrations of PM<sub>2.5</sub> chemical  
267 components in 2017, the Pearson correlation coefficients, NMB, NME, MFB and MFE between  
268 modelled and observed values range from 0.14 to 0.8, -9.0% to 46.7%, 27.0% to 79.6%, -3.8% to  
269 38.6%, 19.9% to 42.3%, respectively.

270 The above statistics show that our model performs reasonably well in simulating lumped  
271 PM<sub>2.5</sub> concentrations, but has a common issue with currently available global emission inventories:  
272 overestimates in the east of model domain and underestimates in the west (Figure S3).<sup>28</sup> To address  
273 this issue, we follow an approach commonly adopted in the field<sup>13</sup> that uses the model output to  
274 calculate the fractional contributions of production- and consumption-based emission to surface  
275 PM<sub>2.5</sub> concentration (Equation [10]).

276 We define a total of ten emission scenarios (Table 1) to estimate the contributions of each  
277 country to PM<sub>2.5</sub> concentrations in NEA from both production and consumption perspectives. In  
278 Scenario 1, we use the production-based emission inventory (EDGAR v6.1) to simulate the  
279 baseline PM<sub>2.5</sub> concentrations. Suppose we define  $C_{s1}$  as the baseline PM<sub>2.5</sub> concentrations  
280 simulated under the baseline scenario (Scenario 1) in which no emissions are excluded,  $C_{s2}$  as  
281 the simulated PM<sub>2.5</sub> concentration under the Scenario 2 in which the emissions in China are  
282 excluded. Therefore, the difference in simulated PM<sub>2.5</sub> concentrations between Scenario 1 and  
283 Scenario 2 ( $C_{s1} - C_{s2}$ ) measures the contribution of production-based emissions in China to PM<sub>2.5</sub>  
284 concentrations in NEA. Similarly, Scenarios 3 and 4 set the production-based emissions in South  
285 Korea and Japan, respectively, to zero to derive the contributions of production-based emissions  
286 in South Korea ( $C_{s1} - C_{s3}$ ) and Japan ( $C_{s1} - C_{s4}$ ), respectively, to PM<sub>2.5</sub> concentrations in NEA.  
287 Scenarios 5, 6, and 7 set the consumption-based emissions induced by the consumption in China,  
288 South Korea, and Japan, respectively, to zero to derive the contributions of the consumption-based  
289 emissions in China ( $C_{s1} - C_{s5}$ ), South Korea ( $C_{s1} - C_{s6}$ ), and Japan ( $C_{s1} - C_{s7}$ ), respectively, to  
290 PM<sub>2.5</sub> concentrations in NEA. Scenarios 8, 9, and 10 are additionally designed to decompose the  
291 contributions from China's production-based emissions to PM<sub>2.5</sub> concentrations in South Korea  
292 and Japan into parts induced by the consumption in South Korea, Japan, and other countries. The  
293 part of transboundary contributions from emissions produced in China but induced by  
294 consumption in South Korea is calculated as the difference between baseline PM<sub>2.5</sub> concentrations  
295 and simulated PM<sub>2.5</sub> concentrations under scenario 8:  $C_{s1} - C_{s8}$ . Similarly, the part induced by  
296 consumption in Japan is calculated as  $C_{s1} - C_{s9}$ . The part induced by consumption outside China  
297 is calculated as  $C_{s1} - C_{s10}$ . Therefore, the part induced by consumption in China is calculated as  
298  $(C_{s1} - C_{s2}) - (C_{s1} - C_{s10}) = (C_{s10} - C_{s2})$ . Finally, the part induced by consumption outside  
299 China, South Korea, and Japan is calculated indirectly as  $(C_{s1} - C_{s2}) - (C_{s1} - C_{s8}) - (C_{s1} -$   
300  $C_{s9}) - (C_{s10} - C_{s2}) = (C_{s1} - C_{s10}) - (C_{s1} - C_{s8}) - (C_{s1} - C_{s9})$ .

301 The fractional contributions associated with the  $i^{\text{th}}$  emission-reduction scenario at the grid  
302 level are calculated as:

303  $F^i = (C_{s1} - C_{si})/C_{s1},$  [10]

304 where  $F^i$  ( $i = 2, 3, \dots, 10$ ) refers to the gridded fractional contributions attributable to the  $i^{\text{th}}$   
305 emission source associated with the  $i^{\text{th}}$  emission-reduction scenario of which the gridded PM<sub>2.5</sub>  
306 concentrations are termed  $C_{si}$ . All the calculations are aggregated to the annual level.

### 307 2.3. Exposure model for calculating PM<sub>2.5</sub> population exposure

308 Exposure to PM<sub>2.5</sub> pollution is associated with multiple health endpoints and is one of the leading  
309 risk factors contributing to disease burden worldwide.<sup>29</sup> We define the PM<sub>2.5</sub> population exposure  
310 in a country as the total doses of PM<sub>2.5</sub> mass inhaled per day by the entire population in that  
311 country. To calculate the exposure, we use an exposure model that takes into account the time  
312 activity patterns, indoor/outdoor air quality, and human inhalation rates. More specifically, we  
313 compute the baseline PM<sub>2.5</sub> population exposure in a country by summing the product of

314 population, inhalation rate, outdoor/indoor PM<sub>2.5</sub> concentrations, and outdoor/indoor time  
315 fractions for all grid cells covering that country:

316  $Baseline\ PE = \sum_g (P_g \times IR \times (PM_{out_g} \times T_{out} + PM_{in_g} \times T_{in})) / 10^9$  [11]

317  $PM_{in_g} = PM_{out_g} \times IF$  [12]

318 where *Baseline PE* refers to the baseline PM<sub>2.5</sub> population exposure with a unit of kg per day,  
319  $P_g$  refers to the population count at the g<sup>th</sup> grid cell, which is obtained from the Worldpop high-  
320 resolution population distribution datasets.<sup>30</sup>  $PM_{out_g}$  refers to the outdoor ambient PM<sub>2.5</sub>  
321 concentration at the g<sup>th</sup> grid cell, which is obtained from a newly available high-resolution  
322 (1 km × 1 km) satellite-derived PM<sub>2.5</sub> concentration dataset.<sup>31</sup> *IR* refers to the inhalation rate that  
323 measures the amount of air inhaled per day (m<sup>3</sup> per day) by people in that country or its different  
324 regions.  $T_{out}$  and  $T_{in}$  refer to the time fractions that people in that country or its different regions  
325 spend in outdoor and indoor environments, respectively. *IR*,  $T_{out}$  and  $T_{in}$  are obtained from the  
326 Chinese exposure factor handbook,<sup>32</sup> updated exposure factors study in South Korea,<sup>33</sup> and Japan  
327 exposure factor handbook,<sup>34</sup> respectively. They are listed in Table S7 and S8.  $PM_{in_g}$  refers to the  
328 indoor PM<sub>2.5</sub> concentration at the g<sup>th</sup> grid cell. *IF* refers to the infiltration factors, which measure  
329 the equilibrium fractions of outdoor particles penetrating indoors and remaining suspended.<sup>35</sup> *IF*  
330 are obtained from the literature<sup>36-38</sup> and are listed in Table S9. The sum of all the combinations of  
331 these terms is expressed in µg because the unit of  $PM_{out_g}$  is µg/m<sup>3</sup>. To obtain a unit of kg, we  
332 divide the sum by 10<sup>9</sup>.

333 We compute the PM<sub>2.5</sub> population exposure in a receptor country contributed by the i<sup>th</sup>  
334 emission source by summing the product of population, inhalation rates, gridded fractional  
335 contribution calculated from Equation [10], outdoor/indoor PM<sub>2.5</sub> concentrations, and  
336 outdoor/indoor time fractions for all grid cells covering that receptor country:

337  $Source\ PE^i = \sum_g (P_g \times IR \times F_g^i \times (PM_{out_g} \times T_{out} + PM_{in_g} \times T_{in})) / 10^9$  [13]

338 The baseline PWM ambient PM<sub>2.5</sub> concentration in a country is calculated as:

339  $Baseline\ PWM = \sum_g (P_g \times PM_{out_g}) / \sum_g (P_g)$  [14]

340 The PWM ambient PM<sub>2.5</sub> concentration in a receptor country contributed by the i<sup>th</sup> emission source  
341 is then calculated as:

342  $Source\ PWM^i = \sum_g (P_g \times F_g^i \times PM_{out_g}) / \sum_g (P_g)$  [15]

343 With baseline and source *PE* and *PWM*, we quantify the relative contributions of PM<sub>2.5</sub>  
344 concentrations and associated population exposure in a receptor country attributable to the i<sup>th</sup>  
345 emission source as:

346  $RC1^i = Source\ PWM^i / Baseline\ PWM$  [16]

347  $RC2^i = Source\ PE^i / Baseline\ PE$  [17]

348 **2.4. Exposure-response model for estimating PM<sub>2.5</sub>-related premature deaths**

349 We use the Meta Regression-Bayesian, Regularized, Trimmed (MR-BRT) model, as developed in  
 350 the GBD-2019 study,<sup>39</sup> to estimate PM<sub>2.5</sub>-related premature deaths. The MR-BRT model  
 351 characterizes the exposure-response relationship across a wide range of ambient PM<sub>2.5</sub>  
 352 concentrations.<sup>39</sup> It is particularly well-suited for studies focusing on Asia, as it incorporates  
 353 additional data from cohort studies conducted in high-pollution, low-income countries such as  
 354 China. In this study, we estimate the number of premature deaths attributable to PM<sub>2.5</sub> pollution  
 355 resulting from adult (25 years and older) ischemic heart disease, stroke, chronic obstructive  
 356 pulmonary disease, type II diabetes, lung cancer, and childhood (younger than 5 years) and adult  
 357 (25 years and older) acute lower respiratory infection. Additionally, we calculate the 95%  
 358 Confidential Intervals (CIs) for our estimates of attributable premature deaths.

359 We estimate the number of premature deaths related to PM<sub>2.5</sub> pollution resulting from adult  
 360 (25 years and older) ischemic heart disease, stroke, chronic obstructive pulmonary disease, type II  
 361 diabetes, lung cancer, and childhood (younger than 5 years) and adult (25 years and older) acute  
 362 lower respiratory infection, using the following equations:

363  $M = \sum_g \sum_d \sum_a M_{a,g}^d$  [18]

364  $M_{a,g}^d = AF_{a,g}^d \times B_a^d \times P_{a,g}$  [19]

365  $AF_{a,g}^d = (RR_a^d (PM_{out_g}) - 1) / RR_a^d (PM_{out_g})$  [20]

366 where  $M$  is the total PM<sub>2.5</sub>-related premature deaths in a receptor country,  $M_{a,g}^d$  is the PM<sub>2.5</sub>-  
 367 related premature deaths for the  $a^{\text{th}}$  age group due to the  $d^{\text{th}}$  disease at the  $g^{\text{th}}$  grid cell in that  
 368 receptor country, and  $AF_{a,g}^d$  is the attributable fraction to PM<sub>2.5</sub> pollution for the  $a^{\text{th}}$  age group and  
 369 the  $d^{\text{th}}$  disease at the  $g^{\text{th}}$  grid cell in that receptor country;  $B_a^d$  is the baseline death incidence due  
 370 to the  $d^{\text{th}}$  disease for the  $a^{\text{th}}$  age group in that receptor country, with its values derived from the  
 371 national average data in the Global Burden of Disease Study 2019 (GBD 2019) database.<sup>40</sup>  
 372  $RR_a^d (PM_{out_g})$  is the relative risk (RR) for the  $a^{\text{th}}$  age group and the  $d^{\text{th}}$  disease due to exposure  
 373 to ambient PM<sub>2.5</sub> pollution at the  $g^{\text{th}}$  grid cell in that receptor country, which is further calculated  
 374 using the MR-BRT model developed in the GBD 2019 study.<sup>39</sup>

375 The MR-BRT model describes the exposure-response relationship for a wide range of  
 376 ambient PM<sub>2.5</sub> concentrations.<sup>39</sup> The relative risk at the  $g^{\text{th}}$  grid cell for the  $a^{\text{th}}$  age group and the  
 377  $d^{\text{th}}$  disease is calculated as:

378  $RR_a^d (PM_{out_g}) = \begin{cases} MRBRT(PM_{out_g}) / MRBRT(tmrel), & PM_{out_g} > tmrel \\ 1 & , PM_{out_g} < tmrel \end{cases}$  [21]

379 where  $tmrel$  is the theoretical minimum risk exposure level (TMREL),  $MRBRT(PM_{out_g})$  and  
 380  $MRBRT(tmrel)$  refer to the estimates of risks when exposed to PM<sub>2.5</sub> concentrations of  $PM_{out_g}$   
 381 and  $tmrel$ , respectively. The GBD 2019 study generates 1000 samples of TMREL estimates with  
 382 a uniform distribution from 2.4 to 5.9  $\mu\text{g}/\text{m}^3$ , and 1000 risk estimates for each PM<sub>2.5</sub> exposure  
 383 interval level and each disease. These estimates, which are provided in the format of look-up  
 384 tables,<sup>41</sup> enable us to calculate the 95% confidential intervals (CIs) of PM<sub>2.5</sub>-related premature  
 385 deaths.

386 To determine the number of premature deaths attributable to the  $i^{\text{th}}$  emission source, we follow  
387 previous studies<sup>14,42-44</sup> and adopt the direct proportion approach, which assumes a linear  
388 relationship between the proportions of PM<sub>2.5</sub> concentration to the proportion of total PM<sub>2.5</sub>-related  
389 premature deaths:

390 
$$\text{Source } M^i = \sum_g \sum_d \sum_a (M_{a,g}^d \times F_g^i) \quad [22]$$

391 where  $\text{Source } M^i$  is the number of PM<sub>2.5</sub>-related premature deaths in a receptor country  
392 attributable to the  $i^{\text{th}}$  emission source.

393 With total PM<sub>2.5</sub>-related premature deaths  $M$  and PM<sub>2.5</sub>-related premature deaths attributable  
394 to the  $i^{\text{th}}$  emission source  $\text{Source } M^i$ , we calculate the relative contribution of PM<sub>2.5</sub>-related  
395 premature deaths in a receptor country attributable to the  $i^{\text{th}}$  emission source as:

396 
$$RC3^i = \text{Source } M^i / M \quad [23]$$

397 In addition, in order to verify whether there are statistically significant differences between  
398 these consumption-based estimates and production-based estimates, we calculate monthly-scale  
399 values for PWM PM<sub>2.5</sub> concentration and PM<sub>2.5</sub> population exposure from both production and  
400 consumption perspectives, and use these results to conduct paired Student t-tests. We do not  
401 calculate monthly-scale PM<sub>2.5</sub>-related premature deaths because the monthly baseline death  
402 incidence data are not available. Therefore, we do not conduct statistical tests for comparing the  
403 consumption-based PM<sub>2.5</sub>-related premature deaths and production-based PM<sub>2.5</sub>-related premature  
404 deaths.

405 **3. Results**

406 **3.1. Local and transboundary contributions to PM<sub>2.5</sub> concentrations between China, South  
407 Korea, and Japan**

408 Figure 1 shows the gridded fractional contributions to PM<sub>2.5</sub> concentrations from production- and  
409 consumption-based emissions in NEA countries in 2017. Results from 2015 are pretty similar and  
410 have therefore been omitted for brevity. The fractional contributions are defined as the ratios of  
411 the differences between the baseline and non-baseline (Table 1) PM<sub>2.5</sub> concentrations to the  
412 baseline PM<sub>2.5</sub> concentrations. We identify three interesting spatial patterns. First, the impacts of  
413 emissions from China, South Korea, and Japan on PM<sub>2.5</sub> concentrations are primarily constrained  
414 within their own borders, regardless of whether viewed from a perspective of production or  
415 consumption. Second, the impacts of production-based (Figure 1A) emissions from upwind  
416 countries on PM<sub>2.5</sub> concentrations in downwind countries due to atmospheric transport are evident.  
417 Third, the footprint of the impacts on PM<sub>2.5</sub> concentrations attributable to consumption-based  
418 emissions is more widely distributed than that attributed to production-based emissions (Figures  
419 1E and 1F versus Figures 1B and 1C). This suggests that trade expands the extent to which  
420 atmospheric transport relocates PM<sub>2.5</sub> pollution among countries by separating production and  
421 consumption activities and allowing the production of emissions to occur far from where the goods  
422 are consumed.

423 Table 2 shows the contributions from source to receptor countries' PWM PM<sub>2.5</sub>  
424 concentrations in NEA in 2015 and 2017. The production perspective shows that the largest  
425 contributors to PWM PM<sub>2.5</sub> concentrations in China, South Korea, and Japan in 2015 are  
426 themselves with local contributions of 72.2%, 38.9%, and 38.7%, respectively. This pattern  
427 persists in 2017 with slightly decreased values of 70.7%, 37.3%, and 37.7% for China, South

428 Korea, Japan, respectively. The consumption perspective suggests that the results for China are  
429 similar as the largest contributor is China itself, but the largest proportions of PWM PM<sub>2.5</sub>  
430 concentrations in South Korea and Japan are contributed by the emissions driven by the  
431 consumption in other countries and natural sources of PM<sub>2.5</sub> (e.g., dust, sea salt, etc.).

432 With respect to transboundary contributions, we find that, in 2015, the emissions produced  
433 (induced by consumption) in China contribute 35.0% (26.9%) and 22.1% (17.6%) to PWM PM<sub>2.5</sub>  
434 concentrations in South Korea and Japan, respectively. Contributions of the emissions produced  
435 (induced by consumption) in South Korea to PWM PM<sub>2.5</sub> concentrations in China and Japan are  
436 relatively low at 0.4% (0.5%) and 3.6% (2.5%), respectively. Contributions of Japan's production-  
437 based (consumption-based) emissions to PWM PM<sub>2.5</sub> concentrations in China and South Korea  
438 are even lower at 0.1% (0.7%) and 0.9% (1.6%), respectively. From 2015 to 2017, there are only  
439 minor changes in these values, suggesting that the results are fairly consistent despite any  
440 differences in emissions, meteorology, and other factors during the two years.

441 We find that the consumption-based PWM PM<sub>2.5</sub> concentrations and production-based PWM  
442 PM<sub>2.5</sub> concentrations are significantly different (Table S10). We also find that consumption-related  
443 contributions from upwind countries to downwind countries (from China to South Korea and  
444 Japan, and from South Korea to Japan) are lower than the corresponding production-related  
445 contributions. Conversely, consumption-related contributions from downwind countries to upwind  
446 countries (from Japan to South Korea and China, and from South Korea to China) are higher than  
447 the corresponding production-related contributions. This suggests that trade narrows the gaps in  
448 mutual contributions of PWM PM<sub>2.5</sub> concentrations among China, South Korea, and Japan, which  
449 becomes even more noticeable when we observe the PM<sub>2.5</sub> population exposure and associated  
450 premature deaths below.

### 451 **3.2. Transboundary contributions to PM<sub>2.5</sub> population exposure between China, South Korea, 452 and Japan**

453 Table 3 shows the SRR of PM<sub>2.5</sub> population exposure among China, South Korea, and Japan. From  
454 a production perspective, China's contributions to PM<sub>2.5</sub> population exposure in South Korea (3.79  
455 and 3.72 kg/d) are 1.3 and 2.8 times those of South Korea to China (2.93 and 1.32 kg/d) in 2015  
456 and 2017, respectively. China's contributions to PM<sub>2.5</sub> population exposure in Japan (2.11 and 2.07  
457 kg/d) are 4.4 and 14.8 times those of Japan to China (0.48 and 0.14 kg/d) in 2015 and 2017,  
458 respectively. South Korea's contributions to PM<sub>2.5</sub> population exposure in Japan (0.34 and 0.37  
459 kg/d) are 3.4 and 6.2 times those of Japan to South Korea (0.1 and 0.06 kg/d) in 2015 and 2017,  
460 respectively.

461 The results calculated from a consumption perspective show a different pattern. Particularly,  
462 China's contributions to PM<sub>2.5</sub> population exposure in South Korea (2.92 and 2.88 kg/d) are 0.7  
463 and 1.1 times those of South Korea to China (3.9 and 2.74 kg/d) in 2015 and 2017, respectively.  
464 China's contributions to PM<sub>2.5</sub> population exposure in Japan (1.68 and 1.68 kg/d) are  
465 approximately 31% and 39% those of Japan to China (5.48 and 4.26 kg/d) in 2015 and 2017,  
466 respectively. South Korea's contributions to PM<sub>2.5</sub> population exposure in Japan (0.24 and 0.27  
467 kg/d) are approximately 1.4 and 1.9 times those of Japan to South Korea (0.17 and 0.14 kg/d) in  
468 2015 and 2017, respectively. In addition, from a consumption perspective, the largest contributor  
469 to PM<sub>2.5</sub> population exposure in South Korea and Japan are not themselves but the emissions driven  
470 by the consumption in the other countries and natural sources of PM<sub>2.5</sub>.

471 Once again, we find that there are significant differences between the consumption-based  
472 PM<sub>2.5</sub> population exposure and production-based PM<sub>2.5</sub> population exposure (Table S11). We

generally find narrower gaps in mutual contributions of PM<sub>2.5</sub> population exposure among China, South Korea, and Japan from a perspective of consumption than production in both years of 2015 and 2017. In addition, Table 3 shows that South Korea and Japan's contributions to PM<sub>2.5</sub> population exposure in China become larger than or comparable to that of China to South Korea and Japan when switching from a perspective of production to consumption.

### **3.3. Transboundary contributions to PM<sub>2.5</sub>-related premature deaths between China, South Korea, and Japan**

The SRR of PM<sub>2.5</sub>-related premature deaths among China, South Korea, and Japan (Table 4) largely follows the pattern of PM<sub>2.5</sub> population exposure. For brevity, we report that in 2015 and 2017, the ratios of China's contributions to PM<sub>2.5</sub>-related premature deaths in South Korea and vice versa are 1.2 (6.02 versus 5.22 thousand premature deaths) and 2.3 (5.73 versus 2.47 thousand premature deaths) from a production perspective, and 0.7 (4.63 versus 6.96 thousand premature deaths) and 0.9 (4.43 versus 5.03 thousand premature deaths) from a consumption perspective. The ratios of China's contributions to PM<sub>2.5</sub>-related premature deaths in Japan and vice versa in 2015 and 2017 are 5.7 (4.92 versus 0.87 thousand premature deaths) and 15.7 (4.56 and 0.29 thousand premature deaths) from a production perspective, and 0.4 (3.91 versus 9.79 thousand premature deaths) and 0.5 (3.69 versus 7.75 thousand premature deaths) from a consumption perspective. The ratios of South Korea's contributions to PM<sub>2.5</sub>-related premature deaths in Japan and vice versa in 2015 and 2017 are 5.3 (0.8 versus 0.15 thousand premature deaths) and 9.3 (0.84 versus 0.09 thousand premature deaths) from a production perspective, and 2.1 (0.56 versus 0.27 thousand premature deaths) and 2.9 (0.61 versus 0.21 thousand premature deaths) from a consumption perspective. In addition, the consumption perspective suggests that the PM<sub>2.5</sub>-related premature deaths in China, South Korea, and Japan are also highly influenced by emissions driven by the consumption in other countries and natural sources of PM<sub>2.5</sub>.

## **4. Discussion**

We provide a contemporary, comprehensive, and quantitative assessment of the SRR of PM<sub>2.5</sub> pollution and associated health impacts among China, South Korea, and Japan in 2015 and 2017. We find that China is the major contributing source country for transboundary PWM PM<sub>2.5</sub> concentrations in South Korea and Japan, while the contributions of South Korea and Japan to PWM PM<sub>2.5</sub> concentrations in China are negligible. This is consistent from both production and consumption perspectives, with the latter showing narrower gaps in mutual contributions than the former. However, the contributions from South Korea and Japan to PM<sub>2.5</sub> population exposure and associated premature deaths in China are non-negligible from both production and consumption perspectives. From a consumption perspective, South Korea and Japan contribute to PM<sub>2.5</sub> population exposure and associated premature deaths in China at levels that are generally larger than China's contributions to South Korea and Japan. This reverses the relationship in mutual contributions of PM<sub>2.5</sub> population exposure and associated premature deaths when viewed from a production perspective. This reversed relationship primarily stems from the differences between the consumption-based emission inventory and production-based emission inventory, as well as the differences in population size between countries. From a production perspective, the emissions produced in China are all China's responsibility. But, from a consumption perspective, Japan and South Korea are responsible for part of the emissions produced in China because that part of emissions are produced to meet the demand driven by the consumption in Japan and South Korea (see Table S12 on the contributions from source to receptor countries' nitrogen oxides (NOx) emissions in Northeast Asia in 2015 for an illustration). Although this part of emissions may only contribute a small fraction to PWM PM<sub>2.5</sub> concentration in China, due to China's large population

519 size, the total health impacts caused to China are non-negligible and larger than China's  
520 contribution to Japan and South Korea.

#### 521 **4.1. Comparisons to prior studies**

522 Comparisons with prior analyses are limited by differences in study areas and periods as well as  
523 differences in data and models adopted. There have been quantifications of the SRR of PM<sub>2.5</sub>  
524 pollution and associated health impacts in Asia.<sup>13,17</sup> However, these analyses use coarse resolution  
525 models that have not been informed by local measurements and have not revealed country-to-  
526 country relationships, making them inadequate to guide local actions. In contrast to previous  
527 studies, we have employed regional models, which are informed by local measurements, to  
528 disclose the SRR of the PM<sub>2.5</sub> concentrations and associated population exposure and premature  
529 deaths among China, South Korea, and Japan in more details. This represents a significant  
530 improvement and will benefit local policymaking.

#### 531 **4.2. Decrease in China's contributions to PM<sub>2.5</sub> pollution in South Korea and Japan**

532 Nonetheless, we select and compare production-based studies (Tables S13 and S14) that have  
533 explicitly quantified China's contributions to PM<sub>2.5</sub> pollution in South Korea and Japan over a  
534 period no less than one year. Figure 2 shows reductions in China's contributions to PM<sub>2.5</sub> pollution  
535 in South Korea and Japan from 2008 to 2017, which roughly coincides with the decreasing  
536 emission trend in China from 2010 to 2017, suggesting the co-benefits of China's clean air actions  
537 for neighboring countries' air quality.

538 However, China's clean air actions mainly rely on the end-of-pipe pollution control measures  
539 of which the benefits will become mostly exhausted by 2030.<sup>45</sup> While China's ambitious carbon  
540 neutrality goals will continuously improve its own and likely surrounding countries' air quality in  
541 the next couples of decades by entailing systematic changes in energy sources and industrial  
542 transformation,<sup>46,47</sup> consumption-side efforts can help boost the process. For instance, the  
543 implementation of the Regional Comprehensive Economic Partnership (RCEP) free trade  
544 agreement in January 2022 presents an opportunity for China, South Korea, and Japan to jointly  
545 develop effective PM<sub>2.5</sub> mitigation strategies, particularly from a consumption side.

#### 546 **4.3. Contributions driven by the consumption in other countries outside Northeast Asia to 547 PM<sub>2.5</sub> pollution and associated health impacts in China, South Korea, and Japan**

548 More importantly, the results for all three metrics from a consumption perspective consistently  
549 show that the PM<sub>2.5</sub> pollution and associated health impacts in all three countries are highly  
550 influenced by the consumption in other countries outside Northeast Asia and the natural sources  
551 of PM<sub>2.5</sub>. Taking South Korea and Japan as an illustration, the consumption perspective shows that  
552 the largest proportion of PM<sub>2.5</sub> pollution and associated health impacts are from the emissions  
553 driven by the consumption in other countries and the natural sources of PM<sub>2.5</sub>. Previous studies  
554 have shown that the contribution of the natural sources for PM<sub>2.5</sub> concentrations in China, South  
555 Korea, and Japan are approximately 10%~24%, 9.9%~10%, and 16.1%~42%, respectively.<sup>48,49</sup>  
556 We can infer that, after deducting the contributions from natural sources, other countries outside  
557 Northeast Asia may have played a non-negligible role in contributing to the PM<sub>2.5</sub> pollution and  
558 associated health impacts in Northeast Asia from a consumption perspective. Moreover, as shown  
559 in Tables 2-4, when shifting the perspective from production to consumption, the contribution  
560 from China decreases while the contribution in the "Others" category from other countries and  
561 natural sources of PM<sub>2.5</sub> increases. The changes in the "Others" category in Tables 2-4 from the  
562 production to the consumption perspective reflect the changes in other countries' contributions

563 from production to consumption, as the contributions from natural sources of PM<sub>2.5</sub> are identical  
564 in both scenarios and hence are cancelled out when we calculate the changes. Therefore, the  
565 general public, the media, and the governments in Northeast Asia should really look beyond this  
566 region but focus on the rest of the world, especially those affluent countries with high  
567 consumption.<sup>13,50</sup>

568 In addition, in order to examine to which extent the consumption in China, South Korea,  
569 Japan, and other countries are responsible for the transboundary PM<sub>2.5</sub> pollution and associated  
570 health impacts transported from China to South Korea and Japan, we construct Scenarios 8, 9, and  
571 10 (Table 1) which subtract the emissions in China induced by the consumption in South Korea,  
572 Japan, and all other countries except China, respectively. These additional scenarios help to  
573 decompose the contributions from China's production-based emissions to PM<sub>2.5</sub> pollution and  
574 associated health impacts in South Korea and Japan into parts induced by the consumption in South  
575 Korea, Japan, and other countries. Table 5 shows the partition of transboundary contributions from  
576 China to PM<sub>2.5</sub> pollution and associated population exposure and premature deaths in South Korea  
577 and Japan. While the consumption in China contributes mostly to transboundary PM<sub>2.5</sub> pollution  
578 and associated population exposure and premature deaths transported from China to South Korea  
579 and Japan, the roles played by the consumption in other countries are non-negligible. The  
580 emissions produced in China but induced by consumption in other countries outside Northeast  
581 Asia in 2015 contribute 23.4% and 23.3% to PM<sub>2.5</sub> pollution and associated population exposure  
582 and premature deaths in South Korea and Japan, respectively. The corresponding values for South  
583 Korea and Japan in 2017 are slightly lower but still non-negligible at 22.1% and 21.5%. Once  
584 again, this highlights that an improved regional air quality requires joint efforts from all relevant  
585 countries.

#### 586 4.4. Limitations and uncertainties

587 Our work has several sources of uncertainties. First, the preparation of consumption-based  
588 emission inventories relies on the production-based emission inventory EDGARv6.1 and the  
589 input-output tables in the MRIO model, so errors in these datasets may propagate to our results.  
590 The uncertainties in the EDGARv6.1 derive from the incomplete knowledge and inaccurate  
591 estimation of anthropogenic activities and emission factors. Studies have shown that the  
592 uncertainties of sulfur dioxide (SO<sub>2</sub>), NO<sub>x</sub>, carbon monoxide (CO), non-methane volatile organic  
593 compound (NMVOC), ammonia (NH<sub>3</sub>), BC, and OC in EDGARv4.3.2 are estimated as  
594 14.4%~47.6%, 17.2%~69.4%, 25.9%~64.6%, 32.7%~73.6%, 186%~294.4%, 46.8%~92%, and  
595 88.7%~153.2%, respectively.<sup>52</sup> EDGARv6.1 likely have a similar but narrower range. The input-  
596 output tables are compiled based on national statistics on GDP, trade and survey data, but the  
597 quality of these data vary across countries and years. Trade data, for example, often have  
598 asymmetries and imbalances, where the sum of exports exceeds the sum of imports.<sup>53</sup> Therefore,  
599 a harmonization calculation process is usually performed to compile the input-output tables.  
600 Several global input-output databases are available, each using different data sources and  
601 harmonization and consolidation procedures, including Eora,<sup>54</sup> GTAP,<sup>55</sup> EXIOBASE,<sup>56</sup> WIOD,<sup>57</sup>  
602 and OECD ICIO.<sup>21</sup> Among these databases, the OECD ICIO database is compiled by OECD, while  
603 all other global input-output databases are compiled by academic researchers.<sup>53</sup> Therefore, OECD  
604 ICIO is regarded as the most authoritative, credible, and robust global input-output database  
605 currently available.<sup>58</sup> In addition, our study has combined the global OECD ICIO dataset with  
606 China's MRIO tables with details on 31 provinces of China, which provides more reliable  
607 estimations of the consumption-based emission inventory.

608 Second, the simulated surface PM<sub>2.5</sub> concentrations are affected by uncertainties in emission  
609 inventories and limitations in air quality modelling. The uncertainties in emission inventories are  
610 described above. The limitations in air quality modelling here refer to the imperfect representation  
611 of atmospheric chemistry and meteorological processes in the GEOS-Chem model. Our current  
612 understanding of many physicochemical mechanisms, such as the formation of secondary organic  
613 aerosols, deposition and scavenging, remains to be improved. Due to the computational intensity  
614 of the GEOS-Chem model, it is not feasible to estimate the uncertainties through sensitivity  
615 analyses.<sup>43</sup> Instead, the impact of uncertainties in emission inventories and limitations in air quality  
616 modelling can be evaluated by comparing the simulated PM<sub>2.5</sub> concentrations against the ground  
617 measurements. As shown in the model performance evaluation, the simulated PM<sub>2.5</sub> concentrations  
618 generally agree well with the ground observations, with R values ranging from 0.71 to 0.75 and  
619 NMB values ranging from 39.0% to 39.9% over different years. To further reduce the error from  
620 the simulation process, the GEOS-Chem model output is only used to estimate the fractional  
621 contributions of production- and consumption-based emissions to the baseline simulated PM<sub>2.5</sub>  
622 concentrations. Then, by multiplying the fractional contributions and a high-resolution satellite-  
623 derived PM<sub>2.5</sub> concentration dataset with relatively small uncertainty<sup>31</sup>, we can obtain a more  
624 accurate estimation of the fractional PM<sub>2.5</sub> concentrations contributed by an emission source.

625 Third, the estimates of PM<sub>2.5</sub> population exposure is affected by uncertainties in the data on  
626 time activity patterns, inhalation rates, and infiltration factors. These data are derived from the  
627 surveys provided in the exposure factor handbooks in China,<sup>32</sup> South Korea,<sup>33</sup> and Japan.<sup>34</sup>  
628 Unfortunately, these exposure handbooks did not provide sufficient information on uncertainties  
629 of these data. The exposure factor handbook in Japan,<sup>34</sup> for example, only provides a short  
630 summary in Japanese and English that presents a single value for outdoor time and inhalation rate.  
631 One study focusing on China assumes a coefficient of variation of 5% for the time activity patterns  
632 of Chinese residents,<sup>36</sup> but we have not found uncertainty information for Japan and South Korea.

633 Lastly, the MR-BRT model may introduce additional uncertainties to our results. The MR-  
634 BRT model developed in the GBD 2019 study is built based on cohort studies from various  
635 countries.<sup>39</sup> However, very few cohort studies have examined the health outcomes of PM<sub>2.5</sub>  
636 pollution in China, South Korea and Japan. The database of cohort studies in the GBD-2019 is still  
637 predominantly composed of western cohort studies. Nonetheless, the MR-BRT model is the most  
638 recent and widely used method for estimating health impacts of ambient air pollution. Compared  
639 with the previous Integrated Exposure Response (IER) model<sup>59</sup> and the Global Exposure Mortality  
640 Model (GEMM) model,<sup>60</sup> the MR-BRT model in the GBD-2019 study incorporates more recent  
641 cohort studies, including those in China and India, which provide more data at high PM<sub>2.5</sub> levels.  
642 In addition, existing concentration-response models generally assume that the composition of  
643 PM<sub>2.5</sub> pollution does not vary with countries and that the toxicity of PM<sub>2.5</sub> pollution at a given  
644 concentration level is equivalent across different components (sulfate, nitrate, ammonium, OC,  
645 and BC). However, the health impacts of PM<sub>2.5</sub> pollution in a region may differ from those in other  
646 regions due to variations in the toxicity of PM<sub>2.5</sub> sources.<sup>61,62</sup> This points to a need for future studies  
647 that take into account the varying toxicity of different PM<sub>2.5</sub> components.

648 **References**

- 649 1. Liu J, Li J, Yao F. Source-receptor relationship of transboundary particulate matter pollution  
650 between China, South Korea and Japan: approaches, current understanding and limitations. *Crit  
651 Rev Environ Sci Technol* 2022; **52**(21): 3896-920. doi:10.1080/10643389.2021.1964308.
- 652 2. Shapiro MA, Yarime M. Effects of national affiliations and international collaboration on  
653 scientific findings: The case of transboundary air pollution in Northeast Asia. *Environ Sci Policy*  
654 2021; **118**: 71-85. doi:10.1016/j.envsci.2021.01.005.
- 655 3. Yim SHL, Gu YF, Shapiro M, Stephens B. Air quality and acid deposition impacts of local  
656 emissions and transboundary air pollution in Japan and South Korea. *Atmospheric Chemistry and  
657 Physics* 2019; **19**(20): 13309-23. doi:10.5194/acp-19-13309-2019.
- 658 4. Oh HR, Ho CH, Koo YS, et al. Impact of Chinese air pollutants on a record-breaking PMs  
659 episode in the Republic of Korea for 11-15 January 2019. *Atmospheric Environment* 2020; **223**:  
660 117262. doi:10.1016/j.atmosenv.2020.117262.
- 661 5. Han X, Cai JZ, Zhang MG, Wang XF. Numerical simulation of interannual variation in  
662 transboundary contributions from Chinese emissions to PM<sub>2.5</sub> mass burden in South Korea.  
663 *Atmospheric Environment* 2021; **256**: 118440. doi:10.1016/j.atmosenv.2021.118440.
- 664 6. Ikeda K, Yamaji K, Kanaya Y, et al. Source region attribution of PM<sub>2.5</sub> mass concentrations  
665 over Japan. *Geochemical Journal* 2015; **49**(2): 185-94. doi:10.2343/geochemj.2.0344.
- 666 7. Choi J, Park RJ, Lee H-M, et al. Impacts of local vs. trans-boundary emissions from different  
667 sectors on PM<sub>2.5</sub> exposure in South Korea during the KORUS-AQ campaign. *Atmospheric  
668 Environment* 2019; **203**: 196-205. doi:10.1016/j.atmosenv.2019.02.008.
- 669 8. Meng J, Liu J, Xu Y, et al. Globalization and pollution: tele-connecting local primary PM<sub>2.5</sub>  
670 emissions to global consumption. *Proceedings of the Royal Society of London A: Mathematical,  
671 Physical and Engineering Sciences* 2016; **472**(2195): 20160380. doi:10.1098/rspa.2016.0380.
- 672 9. Liang S, Qu S, Zhu Z, Guan D, Xu M. Income-Based Greenhouse Gas Emissions of Nations.  
673 *Environmental Science & Technology* 2017; **51**(1): 346-55. doi:10.1021/acs.est.6b02510.
- 674 10. Liang S, Stylianou KS, Jolliet O, et al. Consumption-based human health impacts of primary  
675 PM<sub>2.5</sub>: The hidden burden of international trade. *Journal of Cleaner Production* 2017; **167**: 133-9.  
676 doi:10.1016/j.jclepro.2017.08.139.
- 677 11. Lin J, Pan D, Davis SJ, et al. China's international trade and air pollution in the United States.  
678 *Proceedings of the National Academy of Sciences* 2014; **111**(5): 1736-41.  
679 doi:10.1073/pnas.1312860111.
- 680 12. Meng J, Yang H, Yi K, et al. The Slowdown in Global Air-Pollutant Emission Growth and  
681 Driving Factors. *One Earth* 2019; **1**(1): 138-48. doi:10.1016/j.oneear.2019.08.013.
- 682 13. Zhang Q, Jiang X, Tong D, et al. Transboundary health impacts of transported global air  
683 pollution and international trade. *Nature* 2017; **543**(7647): 705-9. doi:10.1038/nature21712.
- 684 14. Jiang X, Zhang Q, Zhao H, et al. Revealing the hidden health costs embodied in Chinese  
685 exports. *Environmental science & technology* 2015; **49**(7): 4381-8. doi:10.1021/es506121s.
- 686 15. Wang H, Zhang Y, Zhao H, et al. Trade-driven relocation of air pollution and health impacts  
687 in China. *Nature Communications* 2017; **8**(1): 738. doi:10.1038/s41467-017-00918-5.
- 688 16. Ou J, Huang Z, Klimont Z, et al. Role of export industries on ozone pollution and its precursors  
689 in China. *Nature Communications* 2020; **11**(1): 5492. doi:10.1038/s41467-020-19035-x.
- 690 17. Takahashi K, Nansai K, Tohno S, Nishizawa M, Kurokawa J-i, Ohara T. Production-based  
691 emissions, consumption-based emissions and consumption-based health impacts of PM<sub>2.5</sub>  
692 carbonaceous aerosols in Asia. *Atmospheric Environment* 2014; **97**: 406-15.  
693 doi:10.1016/j.atmosenv.2014.04.028.
- 694 18. Monforti Ferrario F, Crippa M, Guizzardi D, et al. EDGAR v6.1 Global Air Pollutant  
695 Emissions. European Commission, Joint Research Centre (JRC). 2022.  
696 <http://data.europa.eu/89h/df521e05-6a3b-461c-965a-b703fb62313e>.

- 697 19. Zheng B, Tong D, Li M, et al. Trends in China's anthropogenic emissions since 2010 as the  
698 consequence of clean air actions. *Atmospheric Chemistry and Physics* 2018; **18**(19): 14095-111.  
699 doi:10.5194/acp-18-14095-2018.
- 700 20. Zheng H, Bai Y, Wei W, et al. Chinese provincial multi-regional input-output database for  
701 2012, 2015, and 2017. *Scientific Data* 2021; **8**(1): 244. doi:10.1038/s41597-021-01023-5.
- 702 21. OECD. OECD Inter-Country Input-Output (ICIO) Tables, 2018 edition. Organisation for  
703 Economic Co-operation and Development. 2018. <https://www.oecd.org/sti/ind/inter-country-input-output-tables.htm>.
- 705 22. Gelaro R, McCarty W, Suárez MJ, et al. The Modern-Era Retrospective Analysis for Research  
706 and Applications, Version 2 (MERRA-2). *Journal of Climate* 2017; **30**(14): 5419-54.  
707 doi:10.1175/JCLI-D-16-0758.1.
- 708 23. Li M, Zhang Q, Kurokawa JI, et al. MIX: a mosaic Asian anthropogenic emission inventory  
709 under the international collaboration framework of the MICS-Asia and HTAP. *Atmospheric  
710 Chemistry and Physics* 2017; **17**(2): 935-63. doi:10.5194/acp-17-935-2017.
- 711 24. Zhang Q, Zheng Y, Tong D, et al. Drivers of improved PM<sub>2.5</sub> air quality in China from 2013  
712 to 2017. *Proceedings of the National Academy of Sciences* 2019; **116**(49): 24463-9.  
713 doi:10.1073/pnas.1907956116.
- 714 25. Liu J, Li W, Li J. Quality screening for air quality monitoring data in China. *Environ Pollut*  
715 2016; **216**: 720-3. doi:10.1016/j.envpol.2016.06.037.
- 716 26. Jiang Z, Jolleys MD, Fu T-M, et al. Spatiotemporal and probability variations of surface PM<sub>2.5</sub>  
717 over China between 2013 and 2019 and the associated changes in health risks: An integrative  
718 observation and model analysis. *Science of The Total Environment* 2020; **723**: 137896.  
719 doi:10.1016/j.scitotenv.2020.137896.
- 720 27. Boylan JW, Russell AG. PM and light extinction model performance metrics, goals, and  
721 criteria for three-dimensional air quality models. *Atmospheric Environment* 2006; **40**(26): 4946-  
722 59. doi:10.1016/j.atmosenv.2005.09.087.
- 723 28. Yao F, Palmer PI. Source Sector Mitigation of Solar Energy Generation Losses Attributable  
724 to Particulate Matter Pollution. *Environmental Science & Technology* 2022; **56**(12): 8619-28.  
725 doi:10.1021/acs.est.2c01175.
- 726 29. Hänninen O, Knol AB, Jantunen M, et al. Environmental Burden of Disease in Europe:  
727 Assessing Nine Risk Factors in Six Countries. *Environmental Health Perspectives* 2014; **122**(5):  
728 439-46. doi:doi:10.1289/ehp.1206154.
- 729 30. Lloyd CT, Chamberlain H, Kerr D, et al. Global spatio-temporally harmonised datasets for  
730 producing high-resolution gridded population distribution datasets. *Big Earth Data* 2019; **3**(2):  
731 108-39. doi:10.1080/20964471.2019.1625151.
- 732 31. van Donkelaar A, Hammer MS, Bindle L, et al. Monthly Global Estimates of Fine Particulate  
733 Matter and Their Uncertainty. *Environmental Science & Technology* 2021; **55**(22): 15287-300.  
734 doi:10.1021/acs.est.1c05309.
- 735 32. Ministry of Environmental Protection. Highlights of the Chinese exposure factors handbook  
736 (Adults). Beijing, China: China Environmental Science Press; 2014.
- 737 33. Yoon H, Seo J, Yoo S-K, et al. Updated general exposure factors for risk assessment in the  
738 Korean population. *Journal of Exposure Science & Environmental Epidemiology* 2022.  
739 doi:10.1038/s41370-022-00437-6.
- 740 34. AIST Research Center for CRM. Japanese Exposure Factors Handbook. National Institute of  
741 Advanced Industrial Science and Technology. 2007.  
742 [https://unit.aist.go.jp/riss/crm/exposurefactors/english\\_summary.html](https://unit.aist.go.jp/riss/crm/exposurefactors/english_summary.html).
- 743 35. Xiang J, Weschler CJ, Wang Q, et al. Reducing Indoor Levels of "Outdoor PM<sub>2.5</sub>" in Urban  
744 China: Impact on Mortalities. *Environmental Science & Technology* 2019; **53**(6): 3119-27.  
745 doi:10.1021/acs.est.8b06878.

- 746 36. Zhang W, Yun X, Meng W, et al. Urban residential energy switching in China between 1980  
747 and 2014 prevents 2.2 million premature deaths. *One Earth* 2021; **4**(11): 1602-13.  
748 doi:10.1016/j.oneear.2021.10.013.
- 749 37. Funasaka K, Furuichi Y, Sakai M. Intrusion of the atmospheric aerosol to indoor air by the  
750 difference in house structure and reference to measures approach from microchemical analysis.  
751 *Journal of the Housing Research Foundation "JUSOKEN"* 2018; **44**: 97-107.  
752 doi:10.20803/jusokenronbunjisen.44.0\_97.
- 753 38. Choi DH, Kang DH. Infiltration of Ambient PM<sub>2.5</sub> through Building Envelope in Apartment  
754 Housing Units in Korea. *Aerosol and Air Quality Research* 2017; **17**(2): 598-607.  
755 doi:10.4209/aaqr.2016.06.0287.
- 756 39. Murray CJL, Aravkin AY, Zheng P, et al. Global burden of 87 risk factors in 204 countries  
757 and territories, 1990–2019: a systematic analysis for the Global Burden of Disease Study 2019.  
758 *The Lancet* 2020; **396**(10258): 1223-49. doi:10.1016/S0140-6736(20)30752-2.
- 759 40. Global Burden of Disease Collaborative Network. Global Burden of Disease Study 2019  
760 (GBD 2019) Results. Institute for Health Metrics and Evaluation (IHME). 2020.  
761 <https://vizhub.healthdata.org/gbd-results/>.
- 762 41. Global Burden of Disease Collaborative Network. Global Burden of Disease Study 2019  
763 (GBD 2019) Particulate Matter Risk Curves. Institute for Health Metrics and Evaluation (IHME).  
764 2021. <https://doi.org/10.6069/KHWH-2703>.
- 765 42. Zhao H, Geng G, Zhang Q, et al. Inequality of household consumption and air pollution-  
766 related deaths in China. *Nature Communications* 2019; **10**(1): 4337. doi:10.1038/s41467-019-  
767 12254-x.
- 768 43. Zhao H, Li X, Zhang Q, et al. Effects of atmospheric transport and trade on air pollution  
769 mortality in China. *Atmospheric Chemistry and Physics* 2017; **17**(17): 10367-81. doi:10.5194/acp-  
770 17-10367-2017.
- 771 44. Chafe Zoë A, Brauer M, Klimont Z, et al. Household Cooking with Solid Fuels Contributes  
772 to Ambient PM<sub>2.5</sub> Air Pollution and the Burden of Disease. *Environmental Health Perspectives*  
773 2014; **122**(12): 1314-20. doi:10.1289/ehp.1206340.
- 774 45. Cheng J, Tong D, Zhang Q, et al. Pathways of China's PM<sub>2.5</sub> air quality 2015–2060 in the  
775 context of carbon neutrality. *National Science Review* 2021; **8**(12): nwab078.  
776 doi:10.1093/nsr/nwab078.
- 777 46. Shi X, Zheng Y, Lei Y, et al. Air quality benefits of achieving carbon neutrality in China.  
778 *Science of The Total Environment* 2021; **795**: 148784. doi:10.1016/j.scitotenv.2021.148784.
- 779 47. Tang R, Zhao J, Liu Y, et al. Air quality and health co-benefits of China's carbon dioxide  
780 emissions peaking before 2030. *Nature Communications* 2022; **13**(1): 1008. doi:10.1038/s41467-  
781 022-28672-3.
- 782 48. Karagulian F, Belis CA, Dora CFC, et al. Contributions to cities' ambient particulate matter  
783 (PM): A systematic review of local source contributions at global level. *Atmospheric Environment*  
784 2015; **120**: 475-83. doi:10.1016/j.atmosenv.2015.08.087.
- 785 49. McDuffie EE, Martin RV, Spadaro JV, et al. Source sector and fuel contributions to ambient  
786 PM<sub>2.5</sub> and attributable mortality across multiple spatial scales. *Nature Communications* 2021;  
787 **12**(1): 3594. doi:10.1038/s41467-021-23853-y.
- 788 50. Nansai K, Tohno S, Chatani S, et al. Affluent countries inflict inequitable mortality and  
789 economic loss on Asia via PM<sub>2.5</sub> emissions. *Environ Int* 2020; **134**: 10.  
790 doi:10.1016/j.envint.2019.105238.
- 791 51. National Institute of Environmental Research (NIER). Summary Report of the 4th stage  
792 (2013–2017) LTP Project, 2019.  
793 [https://nier.go.kr/NIER/cmm/fms/NoLoginFileDown.do;jsessionid=C1A37B9309AC438907222958C0680EF9?atchFileId=FILE\\_00000000029154&fileSn=0](https://nier.go.kr/NIER/cmm/fms/NoLoginFileDown.do;jsessionid=C1A37B9309AC438907222958C0680EF9?atchFileId=FILE_00000000029154&fileSn=0)

52. Crippa M, Guizzardi D, Muntean M, et al. Gridded emissions of air pollutants for the period 1970–2012 within EDGAR v4.3.2. *Earth Syst Sci Data* 2018; **10**(4): 1987-2013. doi:10.5194/essd-10-1987-2018.
53. Tukker A, de Koning A, Owen A, et al. Towards Robust, Authoritative Assessments of Environmental Impacts Embodied in Trade: Current State and Recommendations. *J Ind Ecol* 2018; **22**(3): 585-98. doi:10.1111/jiec.12716.
54. Lenzen M, Kanemoto K, Moran D, Geschke A. Mapping the Structure of the World Economy. *Environmental Science & Technology* 2012; **46**(15): 8374-81. doi:10.1021/es300171x.
55. Peters GP, Minx JC, Weber CL, Edenhofer O. Growth in emission transfers via international trade from 1990 to 2008. *Proceedings of the National Academy of Sciences* 2011; **108**(21): 8903-8. doi:doi:10.1073/pnas.1006388108.
56. Tukker A, Poliakov E, Heijungs R, et al. Towards a global multi-regional environmentally extended input-output database. *Ecological Economics* 2009; **68**(7): 1928-37. doi:10.1016/j.ecolecon.2008.11.010.
57. Dietzenbacher E, Los B, Stehrer R, Timmer M, de Vries G. The Construction of World Input-Output Tables in the WIOD Project. *Economic Systems Research* 2013; **25**(1): 71-98. doi:10.1080/09535314.2012.761180.
58. Giljum S, Wieland H, Lutter S, Eisenmenger N, Schandl H, Owen A. The impacts of data deviations between MRIO models on material footprints: A comparison of EXIOBASE, Eora, and ICIO. *J Ind Ecol* 2019; **23**(4): 946-58. doi:10.1111/jiec.12833.
59. Burnett RT, Pope CA, Ezzati M, et al. An integrated risk function for estimating the global burden of disease attributable to ambient fine particulate matter exposure. *Environmental health perspectives* 2014; **122**(4): 397-403. doi:10.1289/ehp.1307049.
60. Burnett R, Chen H, Szyszkowicz M, et al. Global estimates of mortality associated with long-term exposure to outdoor fine particulate matter. *Proceedings of the National Academy of Sciences* 2018; **115**(38): 9592-7. doi:doi:10.1073/pnas.1803222115.
61. Bell ML, Ebisu K. Environmental Inequality in Exposures to Airborne Particulate Matter Components in the United States. *Environmental Health Perspectives* 2012; **120**(12): 1699-704. doi:10.1289/ehp.1205201.
62. Zou YJ, Jin CY, Su Y, Li JR, Zhu BS. Water soluble and insoluble components of urban PM<sub>2.5</sub> and their cytotoxic effects on epithelial cells (A549) in vitro. *Environ Pollut* 2016; **212**: 627-35. doi:10.1016/j.envpol.2016.03.022.

**Table 1. Definitions of emission scenarios in this study.**

<b>Categories</b>	<b>Scenarios</b>	<b>Definition</b>
Base scenario	Scenario 1 (S1)	Baseline scenario in which production-based emissions from EDGARv6.1 is used and no emissions are excluded
Production-based scenarios	Scenario 2 (S2)	A scenario in which emissions produced in China are excluded
	Scenario 3 (S3)	A scenario in which emissions produced in South Korea are excluded
	Scenario 4 (S4)	A scenario in which emissions produced in Japan are excluded
Consumption-based scenarios	Scenario 5 (S5)	A scenario in which emissions induced by final consumption in China are excluded
	Scenario 6 (S6)	A scenario in which emissions induced by final consumption in South Korea are excluded
	Scenario 7 (S7)	A scenario in which emissions induced by final consumption in Japan are excluded
Additional scenarios	Scenario 8 (S8)	A scenario in which emissions in China induced by final consumption in South Korea are excluded
	Scenario 9 (S9)	A scenario in which emissions in China induced by final consumption in Japan are excluded
	Scenario 10 (S10)	A scenario in which emissions in China induced by final consumption in all other countries except China are excluded

831 Note: EDGARv6.1, the Emissions Database for Global Atmospheric Research v6.1.

**Table 2. Contributions from source to receptor countries' population-weighted mean PM<sub>2.5</sub> concentrations in Northeast Asia.**

Year	Receptor country		China ( $\mu\text{g}/\text{m}^3$ , %)	South Korea ( $\mu\text{g}/\text{m}^3$ , %)	Japan ( $\mu\text{g}/\text{m}^3$ , %)	
	Source country					
2015	Baseline PWM PM <sub>2.5</sub> concentration		49.86 100%	24.92 100%	12.24 100%	
	Source country where pollution is emitted	China	36.01 72.2%	8.73 35.0%	2.71 22.1%	
		South Korea	0.19 0.4%	9.69 38.9%	0.44 3.6%	
		Japan	0.03 0.1%	0.22 0.9%	4.74 38.7%	
		Others	13.63 27.3%	6.28 25.2%	4.35 35.6%	
	Source country where goods are consumed	China	25.88 51.9%	6.71 26.9%	2.15 17.6%	
		South Korea	0.25 0.5%	6.06 24.3%	0.31 2.5%	
		Japan	0.35 0.7%	0.39 1.6%	3.79 31.0%	
		Others	23.38 46.9%	11.76 47.2%	5.99 48.9%	
2017	Baseline PWM PM <sub>2.5</sub> concentration		43.38 100%	22.62 100%	11.56 100%	
	Source country where pollution is emitted	China	30.68 70.7%	8.39 37.1%	2.64 22.9%	
		South Korea	0.08 0.2%	8.44 37.3%	0.48 4.1%	
		Japan	0.01 0.0%	0.13 0.6%	4.35 37.7%	
		Others	12.61 29.1%	5.66 25.0%	4.09 35.3%	
	Source country where goods are consumed	China	22.13 51.0%	6.49 28.7%	2.14 18.5%	
		South Korea	0.17 0.4%	5.68 25.1%	0.35 3.0%	
		Japan	0.27 0.6%	0.31 1.3%	3.45 29.9%	
		Others	20.81 48.0%	10.14 44.9%	5.62 48.6%	

834 Note that the values in the rows of "Others" are residuals after deducting Chinese, South Korean  
835 and Japanese contributions from the baseline. Note: PM<sub>2.5</sub>, fine particulate matter; PWM,  
836 population weighted mean.

**Table 3. Contributions from source to receptor countries' PM<sub>2.5</sub> population exposure in Northeast Asia.**

Year	Receptor country		China (kg/d, %)		South Korea (kg/d, %)		Japan (kg/d, %)	
	Source country							
2015	Baseline PM <sub>2.5</sub> population exposure		768.24	100%	10.83	100%	9.56	100%
	Source country where pollution is emitted	China	557.61	72.6%	3.79	35.0%	2.11	22.1%
		South Korea	2.93	0.4%	4.21	38.9%	0.34	3.6%
		Japan	0.48	0.1%	0.1	0.9%	3.7	38.7%
		Others	207.22	26.9%	2.72	25.2%	3.4	35.6%
	Source country where goods are consumed	China	400.7	52.2%	2.92	26.9%	1.68	17.6%
		South Korea	3.9	0.5%	2.64	24.3%	0.24	2.5%
		Japan	5.48	0.7%	0.17	1.6%	2.96	31.0%
		Others	358.16	46.6%	5.10	47.2%	4.68	48.9%
2017	Baseline PM <sub>2.5</sub> population exposure		680.65	100%	10.04	100%	9.04	100%
	Source country where pollution is emitted	China	484.9	71.2%	3.72	37.1%	2.07	22.9%
		South Korea	1.32	0.2%	3.75	37.3%	0.37	4.1%
		Japan	0.14	0.0%	0.06	0.6%	3.4	37.7%
		Others	194.29	28.6%	2.51	25.0%	3.2	35.3%
	Source country where goods are consumed	China	349.43	51.3%	2.88	28.7%	1.68	18.5%
		South Korea	2.74	0.4%	2.52	25.1%	0.27	3.0%
		Japan	4.26	0.6%	0.14	1.3%	2.7	29.9%
		Others	324.22	47.7%	4.5	44.9%	4.39	48.6%

839 Note that the values in the rows of "Others" are residuals after deducting Chinese, South Korean  
840 and Japanese contributions from the baseline. Note: PM<sub>2.5</sub>, fine particulate matter.

**Table 4. Contributions from source to receptor countries' PM<sub>2.5</sub>-related premature deaths in Northeast Asia.**

Year	Receptor country		China (thousand premature deaths with 95% CI, %)		South Korea (thousand premature deaths, 95% CI, %)		Japan (thousand premature deaths, 95% CI, %)	
	Source country							
2015	Total PM <sub>2.5</sub> -related premature deaths		1386.51 (1263.53, 1507.49) 100%		17.19 (14.74, 19.62) 100%		22.32 (15.89, 28.66) 100%	
Source country where pollution is emitted	China	995.47 (908.63, 1081.18)	71.8%	6.02 (5.16, 6.87)	35.0%	4.92 (3.5, 6.32)	22.0%	
	South Korea	5.22 (4.78, 5.66)	0.4%	6.69 (5.74, 7.64)	38.9%	0.8 (0.58, 1.02)	3.6%	
	Japan	0.87 (0.79, 0.95)	0.1%	0.15 (0.13, 0.18)	0.9%	8.72 (6.25, 11.17)	39.1%	
	Others	384.95 (349.34, 419.7)	27.7%	4.33 (3.71, 4.93)	25.2%	7.88 (5.56, 10.16)	35.3%	
Source country where goods are consumed	China	717.01 (654.28, 778.89)	51.7%	4.63 (3.97, 5.28)	26.9%	3.91 (2.78, 5.01)	17.5%	
	South Korea	6.96 (6.36, 7.56)	0.5%	4.19 (3.59, 4.78)	24.4%	0.56 (0.41, 0.72)	2.5%	
	Japan	9.79 (8.93, 10.64)	0.7%	0.27 (0.23, 0.31)	1.6%	6.96 (4.98, 8.93)	31.2%	
	Others	652.75 (593.96, 710.4)	47.1%	8.10 (6.95, 9.25)	47.1%	10.89 (7.72, 14.01)	48.8%	
2017	Total PM <sub>2.5</sub> -related premature deaths		1247.62 (1129.81, 1363.44) 100%		15.44 (13.07, 17.78) 100%		19.86 (13.75, 25.85) 100%	
Source country where pollution is emitted	China	881.06 (799.07, 961.94)	70.6%	5.73 (4.84, 6.59)	37.1%	4.56 (3.17, 5.91)	22.9%	
	South Korea	2.47 (2.24, 2.7)	0.2%	5.78 (4.89, 6.65)	37.4%	0.84 (0.6, 1.07)	4.2%	
	Japan	0.29 (0.26, 0.32)	0.0%	0.09 (0.07, 0.1)	0.6%	7.52 (5.22, 9.78)	37.9%	
	Others	363.8 (328.25, 398.48)	29.2%	3.84 (3.26, 4.43)	24.9%	6.94 (4.76, 9.09)	35.0%	
Source country where goods are consumed	China	636.64 (577.24, 695.2)	51.0%	4.43 (3.75, 5.1)	28.7%	3.69 (2.57, 4.79)	18.6%	
	South Korea	5.03 (4.55, 5.49)	0.4%	3.89 (3.29, 4.48)	25.2%	0.61 (0.43, 0.78)	3.1%	
	Japan	7.75 (7.02, 8.47)	0.6%	0.21 (0.18, 0.24)	1.4%	5.95 (4.13, 7.75)	30.0%	
	Others	598.2 (540.99, 654.28)	48.0%	6.91 (5.85, 7.96)	44.7%	9.61 (6.63, 12.53)	48.3%	

842 Note that the values in the rows of "Others" are residuals after deducting Chinese, South Korean and Japanese contributions from the baseline.

843 Note: PM<sub>2.5</sub>, fine particulate matter; CI, confidential interval.

**Table 5. Partition of China's transboundary contributions to PM<sub>2.5</sub> pollution and associated population exposure and premature deaths in South Korea and Japan.**

Year	Receptor country	South Korea			Japan		
		Concentration ( $\mu\text{g}/\text{m}^3$ , %)	Population exposure (kg/d, %)	Premature death (thousand premature deaths with 95% CI, %)	Concentration ( $\mu\text{g}/\text{m}^3$ , %)	Population exposure (kg/d, %)	Premature death (thousand premature deaths with 95% CI, %)
Source country							
2015	China's contribution from production perspective	8.73, 100%	3.79, 100%	6.02 (5.16, 6.87), 100%	2.71, 100%	2.11, 100%	4.92 (3.5, 6.32), 100%
	- part induced by China's consumption	6.56, 75.1%	2.85, 75.1%	4.52 (3.88, 5.16), 75.1%	2.04, 75.2%	1.59, 75.2%	3.7 (2.63, 4.75), 75.2%
	- part induced by South Korea's consumption	0.04, 0.5%	0.02, 0.5%	0.03 (0.02, 0.03), 0.5%	0.01, 0.5%	0.01, 0.5%	0.02 (0.02, 0.03), 0.5%
	- part induced by Japan's consumption	0.09, 1.0%	0.04, 1.0%	0.06 (0.05, 0.07), 1.0%	0.03, 1.0%	0.02, 1.0%	0.05 (0.04, 0.06), 1.0%
	- part induced by others' consumption	2.04, 23.4%	0.89, 23.4%	1.41 (1.21, 1.61), 23.4%	0.63, 23.3%	0.49, 23.3%	1.15 (0.82, 1.47), 23.3%
2017	China's contribution from production perspective	8.39, 100%	3.72, 100%	5.73 (4.84, 6.59), 100%	2.64, 100.0%	2.07, 100%	4.56 (3.17, 5.91), 100%
	- part induced by China's consumption	6.42, 76.5%	2.85, 76.5%	4.38 (3.7, 5.04), 76.5%	2.04, 77.1%	1.59, 77.1%	3.51 (2.44, 4.55), 77.1%
	- part induced by South Korea's consumption	0.04, 0.5%	0.02, 0.5%	0.03 (0.02, 0.03), 0.5%	0.01, 0.5%	0.01, 0.5%	0.02 (0.01, 0.03), 0.5%
	- part induced by Japan's consumption	0.08, 0.9%	0.03, 0.9%	0.05 (0.04, 0.06), 0.9%	0.02, 0.9%	0.02, 0.9%	0.04 (0.03, 0.05), 0.9%
	- part induced by others' consumption	1.85, 22.1%	0.82, 22.1%	1.27 (1.07, 1.46), 22.1%	0.57, 21.5%	0.45, 21.5%	0.98 (0.69, 1.27), 21.5%

846 Note that the percentages for concentration, population exposure, and premature deaths are slightly different but become identical after  
 847 rounding. Note: PM<sub>2.5</sub>, fine particulate matter; CI, confidential interval.

848 **Figures captions**  
849

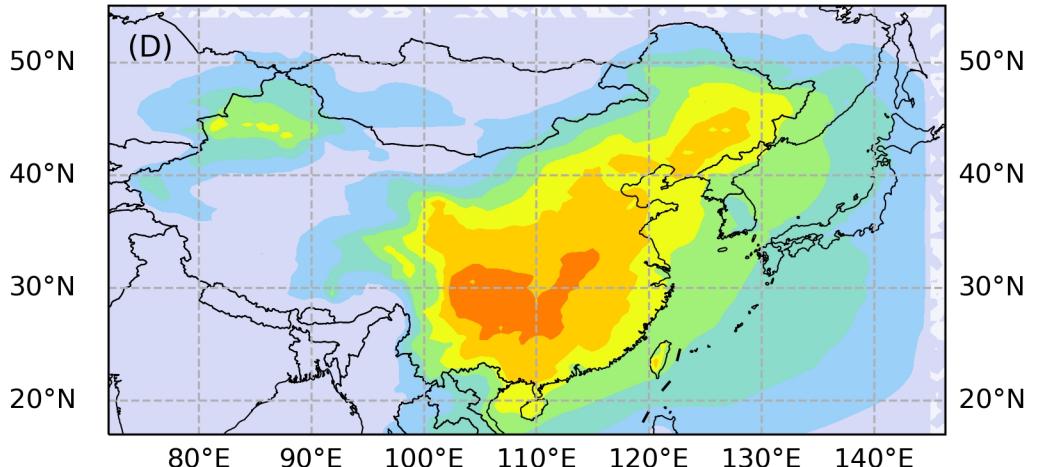
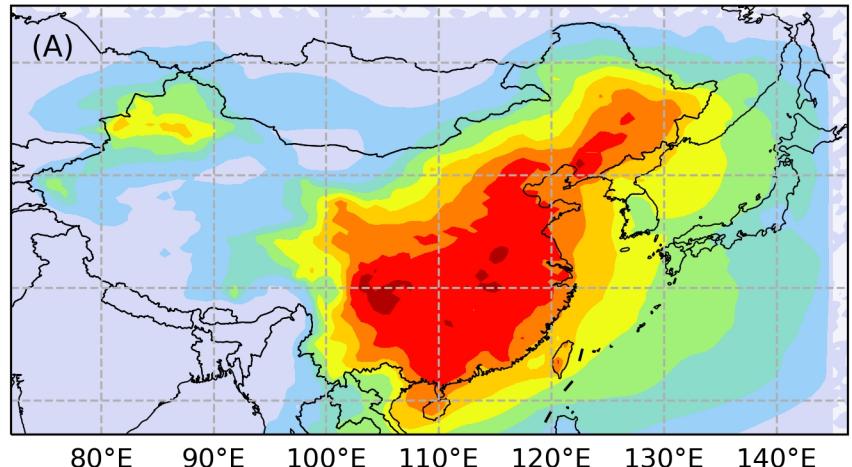
850 **Fig. 1. Annual gridded fractional contributions to PM<sub>2.5</sub> concentrations in 2017 in**  
851 **Northeast Asia from production-based emissions in China (A), South Korea**  
852 **(B), Japan (C), and consumption-based emissions induced by the consumption**  
853 **in China (D), South Korea (E), and Japan (F).** Note: PM<sub>2.5</sub>, fine particulate  
854 matter.

855  
856 **Fig. 2. The estimated PM<sub>2.5</sub> concentrations contributed by China to South Korea (A)**  
857 **and Japan (B) from 2008 to 2017 and the primary PM<sub>2.5</sub> emission trend in**  
858 **China from 2010 to 2017.** Each blue triangle represents an estimation of China's  
859 contribution to PM<sub>2.5</sub> concentrations in South Korea from the literature and this  
860 study. Each blue diamond represents an estimation of China's contribution to PM<sub>2.5</sub>  
861 concentrations in Japan from the literature and this study. The blue dash lines refer  
862 to the trend lines of China's contributions to PM<sub>2.5</sub> concentrations in South Korea  
863 and Japan. The orange line refers to the primary PM<sub>2.5</sub> emission trend in China from  
864 2010 to 2017 based on data obtained from the study by Zheng, Tong<sup>19</sup>. Numeric  
865 data can be found in Table S13, Table S14, and Excel Table S1 in the Supplemental  
866 Excel File. Note: PM<sub>2.5</sub>, fine particulate matter.

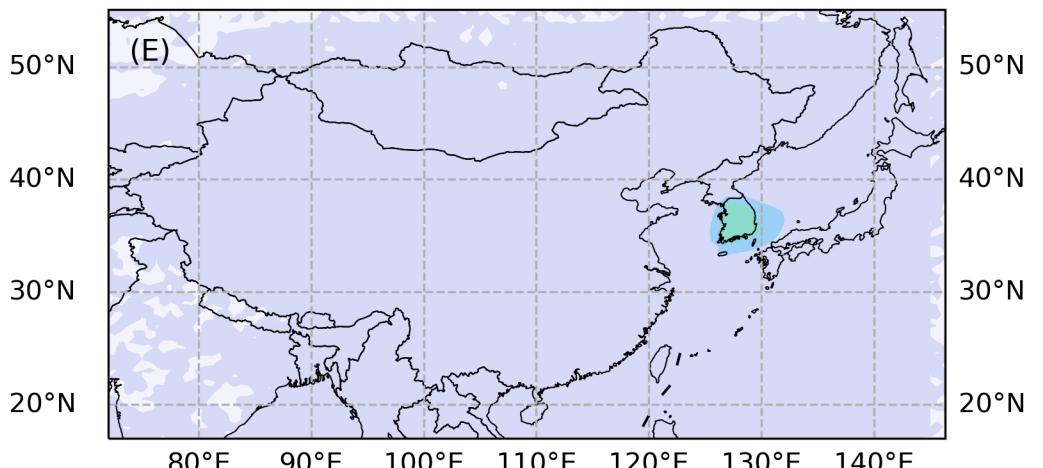
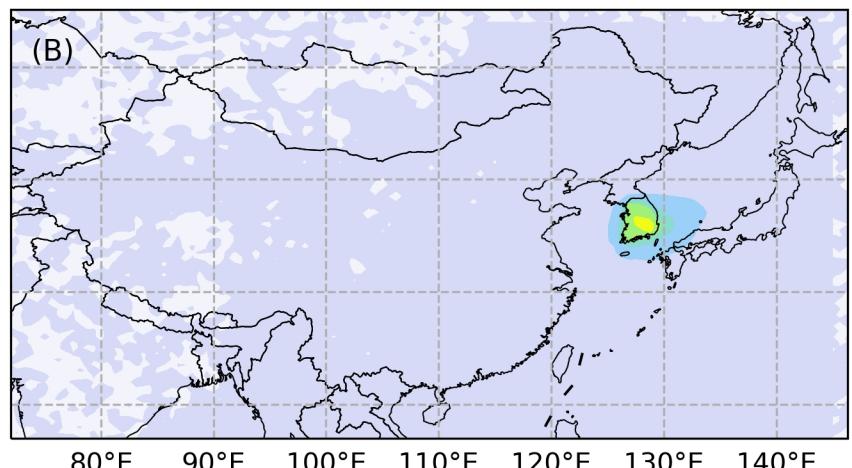
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Consumption-related

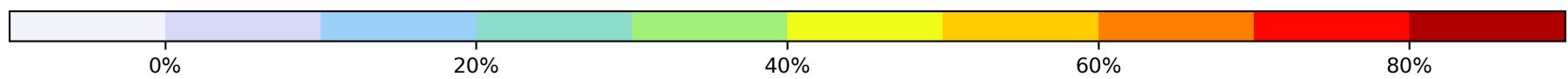
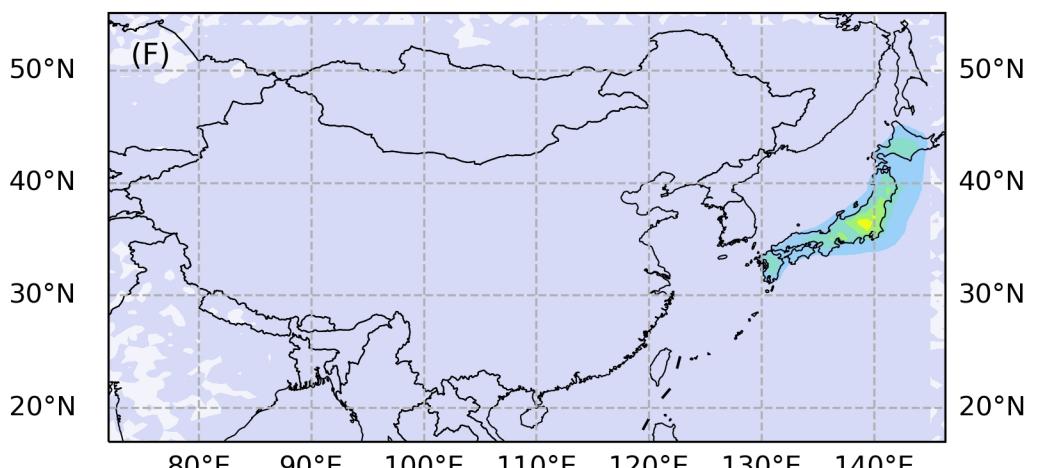
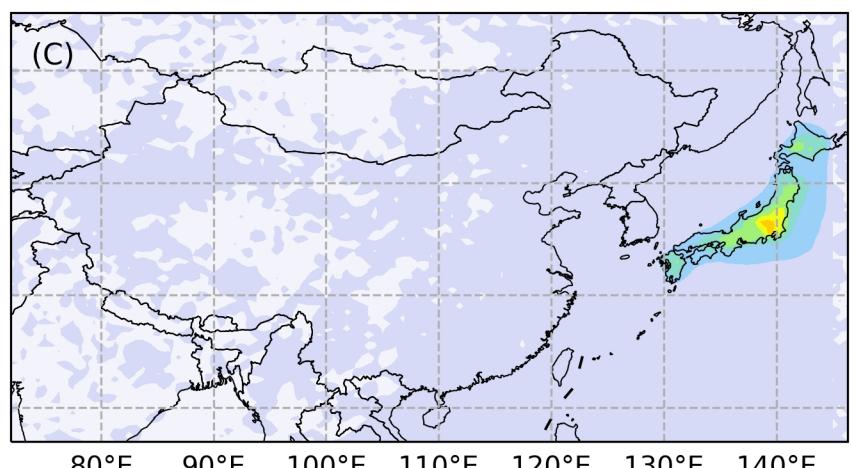
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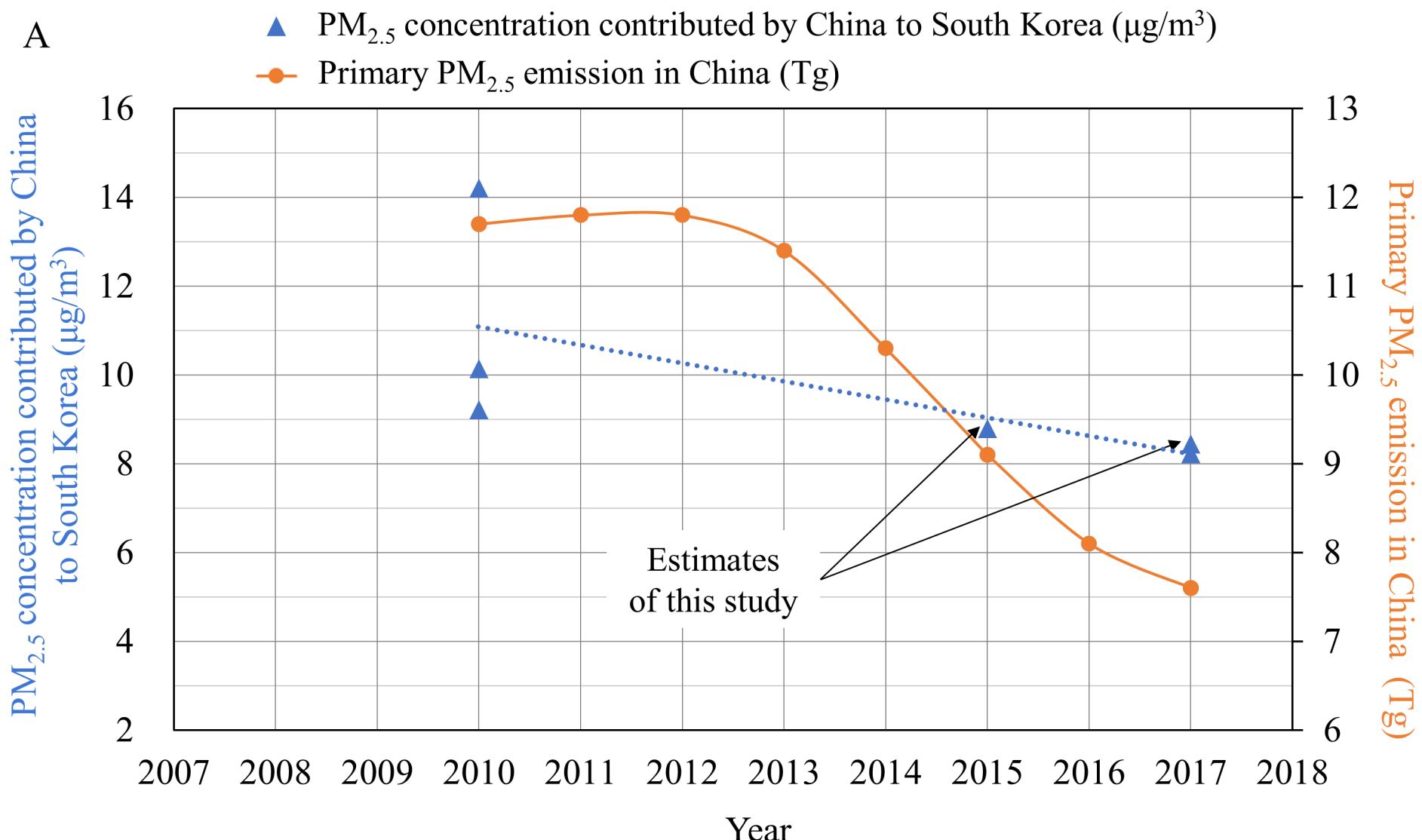
South Korea



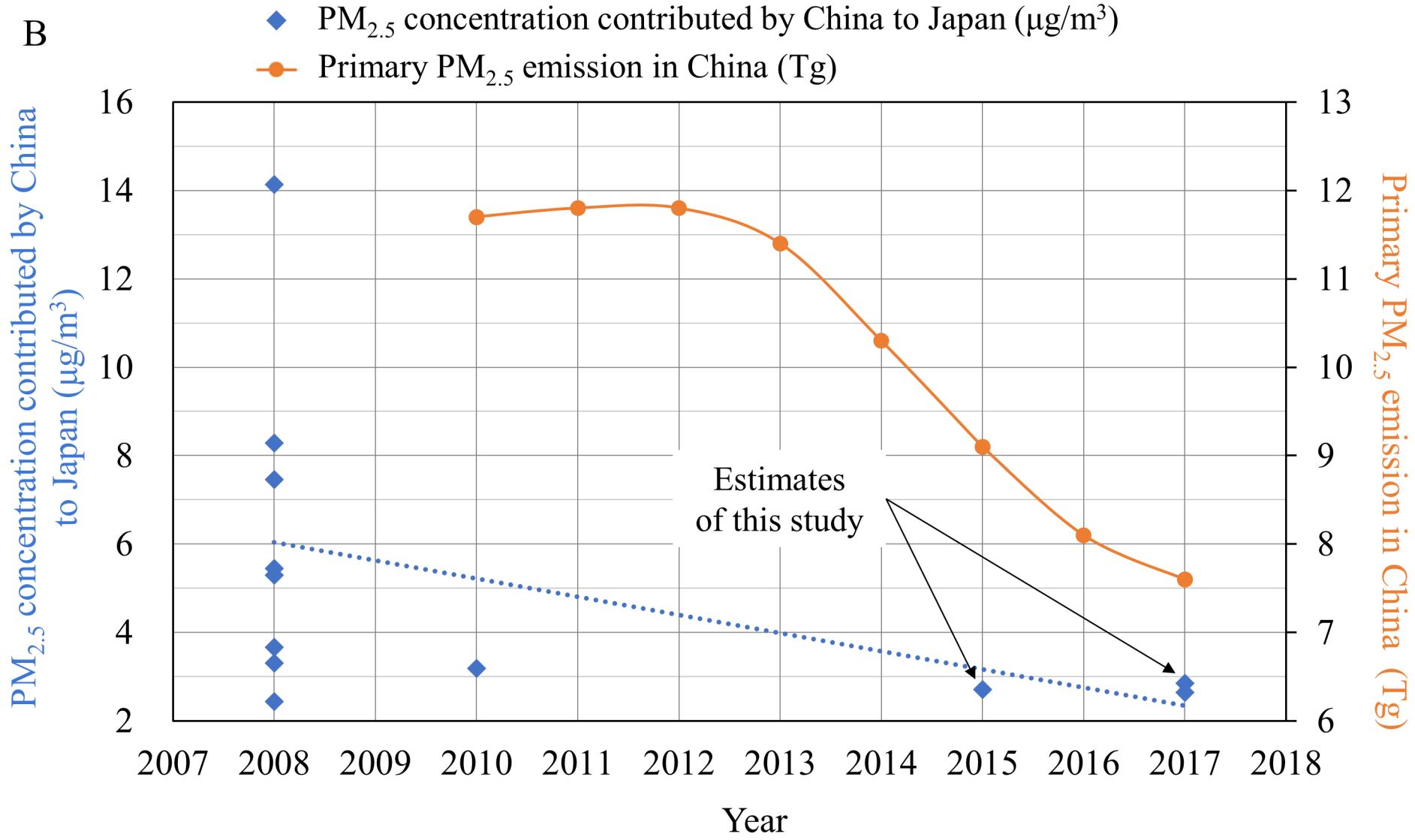
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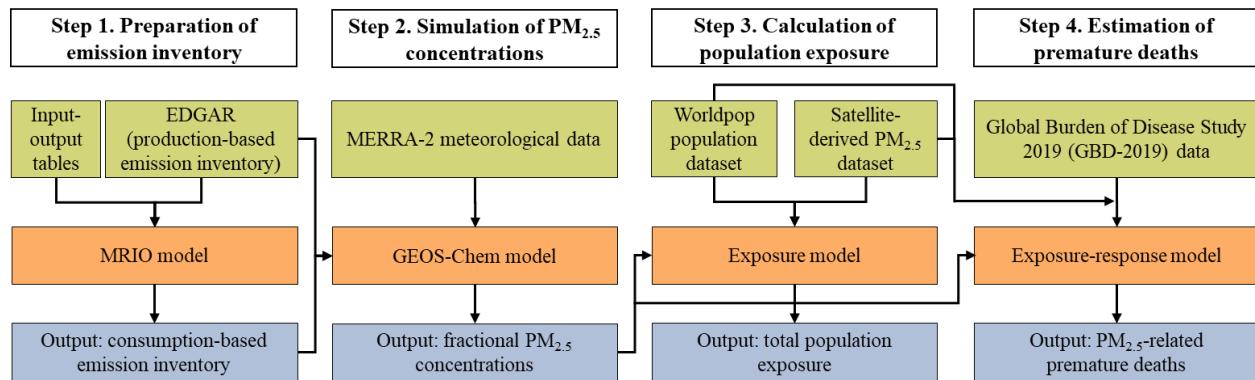


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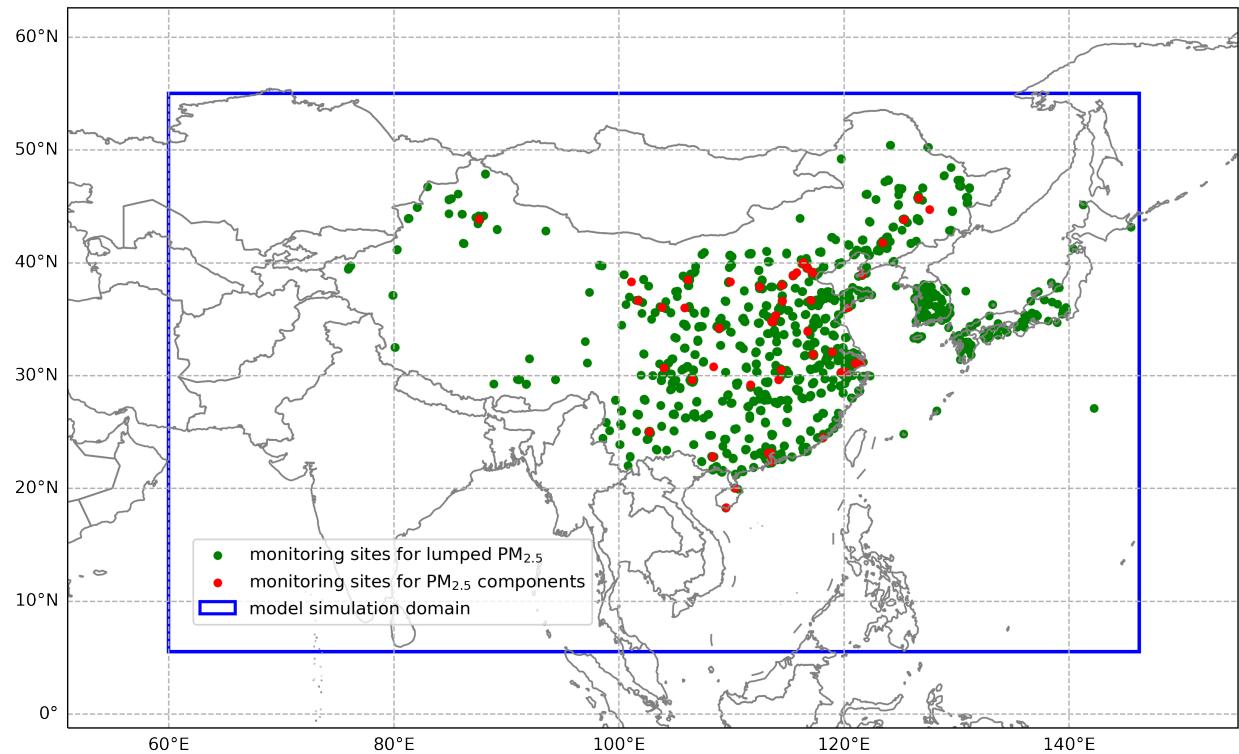
1	<b>Supplementary material for</b>
2	<b>Quantifying the mutual contributions of PM<sub>2.5</sub> pollution and associated population</b>
3	<b>exposure and premature deaths among China, South Korea, and Japan: A dual perspective</b>
4	<b>and an interdisciplinary approach</b>
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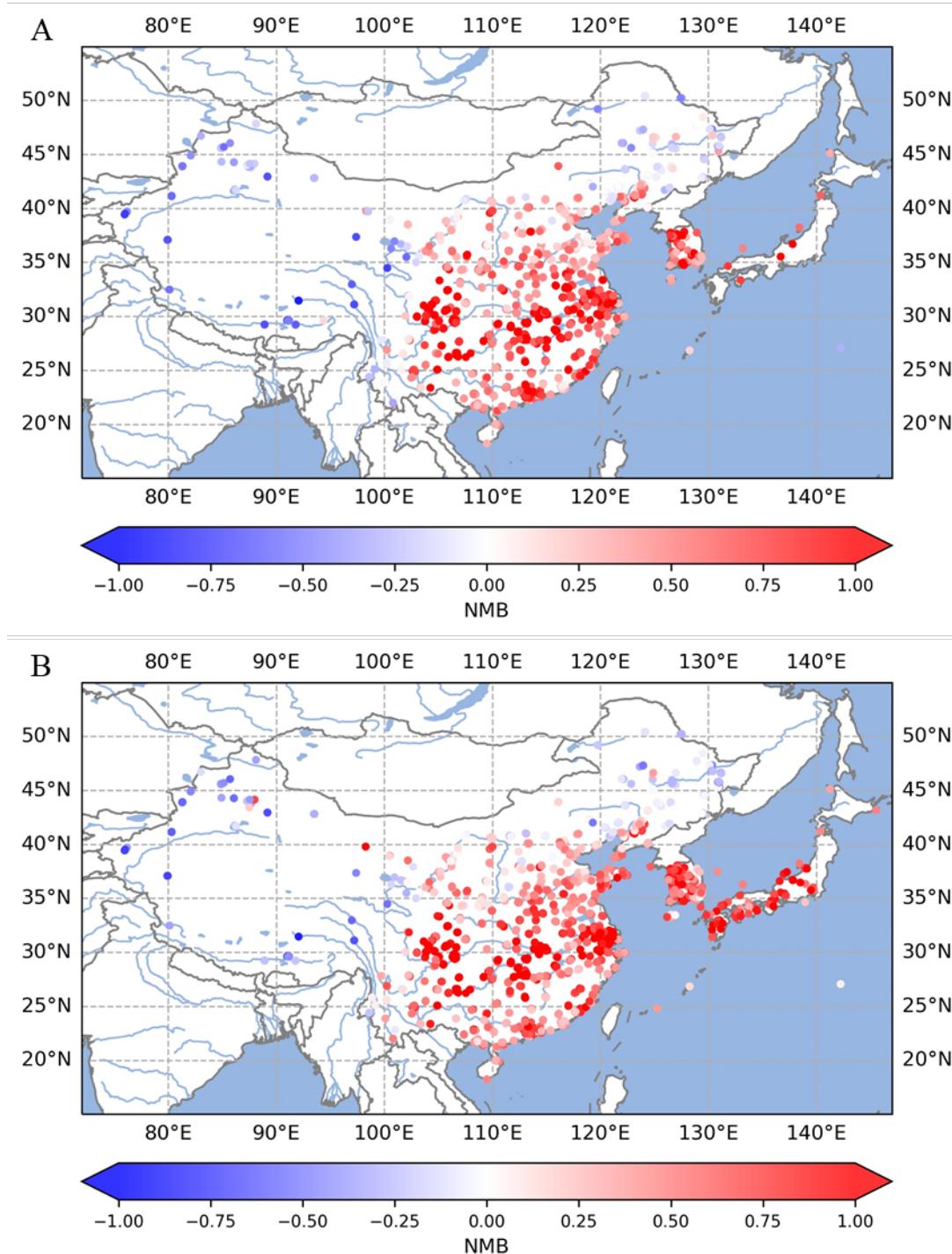
36

37 **Figure S1. Analysis framework in this study. Each column shows the purpose, input data, model, and output**  
 38 **data of each step from top to bottom. Arrows indicate data flow. Note: EDGAR, the Emissions Database for**  
 39 **Global Atmospheric Research; MRIO, multi-regional input-output; PM<sub>2.5</sub>, fine particulate matter; MERRA-2,**  
 40 **Modern-Era Retrospective analysis for Research and Applications version 2; GBD, global burden of disease.**



41

42 **Figure S2. Study domain.** Each green dot represents a monitoring site for lumped PM<sub>2.5</sub>. Each red dot represents a  
 43 monitoring site for PM<sub>2.5</sub> components. Numeric data can be found in Excel Table S2 in the Supplemental  
 44 Excel File. Note: PM<sub>2.5</sub>, fine particulate matter.



45

46 **Figure S3. Site-scale evaluation of simulated monthly average  $\text{PM}_{2.5}$  against ground-level measurements in**  
 47 **terms of normalized mean bias (NMB) in 2015 (A) and 2017 (B).** Each dot represent a monitoring site.  
 48 Numeric data can be found in Excel Table S3 in the Supplemental Excel File. Note:  $\text{PM}_{2.5}$ , fine particulate  
 49 matter; NMB, normalized mean bias.

50

52 **Table S1. The MRIO model.**

			Intermediate demand						Final demand						Total output
			P <sub>1</sub>	...	P <sub>31</sub>	R <sub>1</sub>	...	R <sub>64</sub>	P <sub>1</sub>	...	P <sub>31</sub>	R <sub>1</sub>	...	R <sub>64</sub>	
Intermediate input	Provinces	P <sub>1</sub>	(A)			(D)			(B)			(E)			(C)
		P <sub>2</sub>													
		...													
		P <sub>31</sub>													
	Countries	R <sub>1</sub>	(F)			(I)			(G)			(J)			(H)
		R <sub>2</sub>													
		...													
		R <sub>64</sub>													

53 Note that P<sub>m</sub> refers to province m in China, and R<sub>n</sub> refers to country/region n in this table.54 Parts (A), (B), and (C) in the above table indicate the intermediate demand matrix, the final demand matrix, and  
55 the total output vector in China's MRIO table, respectively. Part (D) and Part (E) in the above table were calculated  
56 using the following equations [1] and [2], respectively:

57 
$$Z_{CAij}^r = EX\_M_i^r * \frac{Z\_IC_{CAij}}{\sum_j Z\_IC_{CAij} + Y\_IC_{CAik} + \sum_R \sum_j Z\_IC_{CRij} + \sum_R Y\_IC_{CRik}} \quad [1]$$

58 
$$Y_{CAik}^r = EX\_M_i^r * \frac{Y\_IC_{CAik}}{\sum_j Z\_IC_{CAij} + Y\_IC_{CAik} + \sum_R \sum_j Z\_IC_{CRij} + \sum_R Y\_IC_{CRik}} \quad [2]$$

59 where  $Z_{CAij}^r$  refers to the result matrix in Part (D), and  $Y_{CAik}^r$  refers to the result matrix in Part (E).  $EX\_M_i^r$   
60 represents the export vector in China's MRIO table.  $Z\_IC_{CAij}$  and  $Y\_IC_{CAik}$  represent, the intermediate demand  
61 and final demand matrices of China, respectively, to any other 64 countries (regions) in the OECD ICIO table.  
62  $Z\_IC_{CRij}$  and  $Y\_IC_{CRik}$  represent, the intermediate demand and final demand matrices of China, respectively, to the  
63 remaining 63 countries (regions)in the OECD ICIO table. Note that the subscripts of C, A, and R represent China,  
64 any other 64 countries (regions), and the remaining 63 countries (regions), respectively. The subscripts of i and j  
65 denote the sectors, and k indicates different types of final demand, including consumption by rural and urban  
66 residents, government investment, fixed asset investment, and others. The superscript of r represents the provinces in  
67 China.

68 Part (F) and Part (G) in the above table were calculated using the following equations [3] and [4], respectively:

69 
$$Z_{ACij}^r = IM\_M_z^r * \frac{Z\_IC_{ACij}}{\sum_i Z\_IC_{ACij} + \sum_R \sum_i Z\_IC_{RCij}} \quad [3]$$

70 
$$Y_{ACik}^r = IM\_M_y^r * \frac{Y\_IC_{ACik}}{\sum_i Y\_IC_{ACik} + \sum_R \sum_i Y\_IC_{RCik}} \quad [4]$$

71 where  $Z_{ACij}^r$  refers to the result matrix in Part (F), and  $Y_{ACik}^r$  refers to the result matrix in Part (G).  $IM\_M_z^r$  and  
72  $IM\_M_y^r$  denote the intermediate and final import vectors in China's MRIO table, respectively.

73 Part (H) in the above table was calculated using the following equation:

74 
$$X_{Ai} = X\_IC_{Ai} * \frac{\sum_r X\_M_i^r}{X\_IC_{Ci}} \quad [5]$$

75 where  $X_{A_i}$  refers to the result matrix in Part (H).  $X\_IC_{C_i}$  and  $X\_IC_{A_i}$  indicate the output vector of China, and any  
76 other 64 countries (regions) in the OECD ICIO table.  $X\_M_i^r$  indicate the total output vector in China's MRIO table.

77 Part (I) and Part (J) in the above table were calculated using the following equations:

$$78 Z_{AA_{ij}} = (X_{A_i} - \sum_j Z_{AC_{ij}}^r - Y_{AC_{ik}}^r) * \frac{Z\_IC_{AA_{ij}}}{\sum_j Z\_IC_{AA_{ij}} + \sum_R \sum_j Z\_IC_{AR_{ij}} + Y\_IC_{AA_{ik}} + \sum_R Y\_IC_{AR_{ik}}} \quad [6]$$

$$79 Y_{AA_{ij}} = (X_{A_i} - \sum_j Z_{AC_{ij}}^r - Y_{AC_{ik}}^r) * \frac{Y\_IC_{AA_{ik}}}{\sum_j Z\_IC_{AA_{ij}} + \sum_R \sum_j Z\_IC_{AR_{ij}} + Y\_IC_{AA_{ik}} + \sum_R Y\_IC_{AR_{ik}}} \quad [7]$$

80 Note: MRIO, multi-regional input-output; PM<sub>2.5</sub>, fine particulate matter; OECD, the Organization for Economic  
81 Cooperation and Development; ICIO, inter-country input-output.

82 **Table S2. Mapping good sectors between China's MRIO table and OECD ICIO table**

The MRIO model	China's MRIO table	OECD ICIO table
Agriculture	Agriculture, forestry and fishery products	Agriculture, forestry and fishing
Mining	Coal mining and processing products	Mining and extraction of energy producing products
	Oil and gas mining products	Mining and quarrying of non-energy producing products
	Metal mining and processing products	Mining support service activities
	Non-metallic minerals	
Food and tobacco	Food and tobacco	Food products, beverages and tobacco
Textiles and Clothes	Textile	Textiles, wearing apparel, leather and related products
	Textile clothing, shoes, hats, leather	
Wood and furniture	Wood products and furniture	Wood and products of wood and cork
Paper printing	Paper making, printing, cultural, educational and sports goods	Paper products and printing
Coke and petroleum	Petroleum, coking products and nuclear fuel processing products	Coke and refined petroleum products
Chemicals	Chemical products	Chemicals and pharmaceutical products
		Rubber and plastic products
Non-metallic mineral	Non-metallic mineral products	Other non-metallic mineral products
Metals	Metal smelting products	Basic metals
	Metal products	Fabricated metal products
General equipment	General equipment, special equipment	Machinery and equipment, n.e.c.
Electrical and optical equipment	Electrical machinery and equipment	Computer, electronic and optical products
	Communication equipment, computers and other electronic equipment	Electrical equipment
	Instruments and meters	
Transport equipment	Transportation equipment	Motor vehicles, trailers and semi-trailers
		Other transport equipment
Other manufacturing	Other manufacturing products	Other manufacturing; repair and installation of machinery and equipment
	Scrap	
	Metal products, equipment repair services	
Electricity	Production and supply of electricity	Electricity, gas, water supply, sewerage, waste and remediation services
	Production and supply of heat and gas	
	Production and supply of water	

83 Note: MRIO, multi-regional input-output; OECD, the Organization for Economic Cooperation and Development;  
 84 ICIO, inter-country input-output.

85 **Table S3. Mapping construction and service sectors between China's MRIO table and OECD ICIO table**

The MRIO model	China's MRIO table	OECD ICIO table
Construction	Construction	Construction
Wholesale and retail trade	Wholesale and retail	Wholesale and retail trade; repair of motor vehicles
Hotels and restaurants	Accommodation and catering	Accommodation and food services
Transport, postage, and warehousing	Transportation, warehousing and post	Transportation and storage Telecommunications
Other services	Others	Publishing, audiovisual and broadcasting activities
		IT and other information services
		Financial and insurance activities
		Real estate activities
		Other business sector services
		Public administration and defence; compulsory social security
		Education
		Human health and social work
		Arts, entertainment, recreation and other service activities
		Private households with employed persons

86 Note: MRIO, multi-regional input-output; OECD, the Organization for Economic Cooperation and Development;  
 87 ICIO, inter-country input–output.

88      **Table S4. Re-organization of the emission sources in EDGARv6.1 into 20 sectors in the MRIO model.** Note  
 89      that household direct emissions from residential sectors in the EDGARv6.1 are considered to be driven by local  
 90      direct consumption and are thus not mapped to any MRIO sectors.

The MRIO model	EDGARv6.1
Agriculture	Manure management
	Rice cultivation
	Direct soil emissions
	Manure in pasture/range/paddock
	Other direct soil emissions
	Agricultural waste burning
Mining	Fugitive emissions from solid fuels
	Fugitive emissions from oil and gas
	Fossil fuel fires
	Fugitive emissions from gaseous fuels
	Fugitive emissions from liquid fuels
Food and tobacco	Production of pulp/paper/food/drink
Textiles and Clothes	Manufacturing Industries and Construction
Wood and furniture	Manufacturing Industries and Construction
Paper printing	Production of pulp/paper/food/drink
Coke and petroleum	Other Energy Industries
Chemicals	Soda ash production and use
	Production of chemicals
	Solvent and other product use: degrease
	Solvent and other product use: other
	Solvent and other product use: paint
	Solvent and other product use: chemicals
Non-metallic mineral	Cement production
	Lime production
	Production of other minerals
Metals	Production of metals
General equipment	Manufacturing Industries and Construction
Electrical and optical equipment	Semiconductor/electronics manufacture
	Electrical equipment
Transport equipment	Manufacturing Industries and Construction
Other manufacturing	Solid waste disposal on land
	Waste incineration
	Wastewater handling
	Other waste handling
Electricity	Public electricity and heat production
Construction	Manufacturing Industries and Construction
Transport, postage, and warehousing	Domestic aviation
	Road transportation no resuspension
	Road transportation resuspension
	Rail transportation

	Inland navigation
	Other transportation
Wholesale and retail trade	Residential and other sectors
Hotels and restaurants	
Other services	
Household direct emissions	

91 Note: EDGARv6.1, the Emissions Database for Global Atmospheric Research v6.1; MRIO, multi-regional input-  
 92 output; OECD, the Organization for Economic Cooperation and Development; ICIO, inter-country input–output.

93 **Table S5. Other GEOS-Chem default emissions used in this study**

Emissions	References
Emissions from aircraft	Stettler, Eastham and Barrett <sup>1</sup>
Emissions from open fires from tropical deforestation, boreal forest, peat, savannah, and temperate forest	van der Werf, Randerson <sup>2</sup>
Emissions from soil	Hudman, Moore <sup>3</sup>
Emissions from lightning	Murray, Jacob <sup>4</sup>
Emissions from nitrogen oxides, biogenic volatile organic compounds	Guenther, Jiang <sup>5</sup>
Emissions from ammonia	Bouwman, Lee <sup>6</sup>
Emissions from volcanic sulfur dioxide	Carn, Yang <sup>7</sup>
Emissions from mineral	Zender, Bian and Newman <sup>8</sup>
Emissions from anthropogenic dust	Philip, Martin <sup>9</sup>
Emissions from oceanic sea salt	Gong <sup>10</sup> , Jaeglé, Quinn <sup>11</sup>
Emissions from the remaining emission sources	Riddick, Dragosits <sup>12</sup> , Liang, Stolarski <sup>13</sup> , Ordóñez, Lamarque <sup>14</sup> , Millet, Guenther <sup>15</sup> , Johnson <sup>16</sup> , Nightingale, Malin <sup>17</sup> , Vinken, Boersma <sup>18</sup> , Holmes, Prather and Vinken <sup>19</sup> , Sherwen, Evans <sup>20</sup>

94

95

96 **Table S6. Model evaluation against ground measurements for lumped PM<sub>2.5</sub> and its components.**

<b>Year</b>	<b>Species</b>	<b>N</b>	<b>R</b>	<b>NMB</b>	<b>NME</b>	<b>MFB</b>	<b>MFE</b>
2015	lumped PM <sub>2.5</sub>	486	0.71	39.0%	49.0%	20.2%	28.7%
	sulfate	58	0.49	34.6%	45.9%	22.6%	28.0%
	nitrate	58	0.69	1.5%	30.5%	4.8%	23.9%
	ammonium	58	0.67	33.6%	41.7%	29.1%	32.4%
	organic carbon	57	0.57	-12.7%	43.8%	-1.2%	30.4%
	black carbon	61	0.48	-6.0%	58.8%	7.4%	44.2%
2017	lumped PM <sub>2.5</sub>	537	0.75	39.9%	49.4%	21.9%	29.1%
	sulfate	38	0.24	68.4%	79.6%	38.6%	42.3%
	nitrate	38	0.8	-9.0%	27.0%	-3.8%	19.9%
	ammonium	38	0.58	46.7%	52.3%	35.3%	37.4%
	organic carbon	37	0.14	1.1%	53.7%	6.9%	35.2%
	black carbon	38	0.57	26.2%	41.7%	14.9%	25.6%

97 Note: PM<sub>2.5</sub>, fine particulate matter; R, pearson correlation coefficient; NMB, normalized mean bias; NME,  
 98 normalized mean error; MFB, mean fractional bias; MFE, mean fractional error.

99 **Table S7. Inhalation rates used in this study**

Region/Country	Inhalation rate ( $\text{m}^3/\text{d}$ )	References
Beijing, China	16.1	
Tianjin, China	16.2	
Hebei, China	16	
Shanxi, China	16.1	
Inner Mongolia, China	16.3	
Liaoning, China	16.3	
Jilin, China	16.2	
Heilongjiang, China	16	
Shanghai, China	15.8	
Jiangsu, China	15.4	
Zhejiang, China	15.6	
Anhui, China	15.4	
Fujian, China	15.5	
Jiangxi, China	15.2	
Shandong, China	16.1	
Henan, China	15.6	Ministry of Environmental Protection <sup>21</sup>
Hubei, China	15.8	
Hunan, China	15.8	
Guangdong, China	15	
Guangxi, China	15.1	
Hainan, China	15.3	
Chongqing, China	14.8	
Sichuan, China	15.4	
Guizhou, China	15.6	
Yunnan, China	15.5	
Tibet, China	15.3	
Shaanxi, China	15.1	
Gansu, China	15.6	
Qinghai, China	16	
Ningxia, China	16	
Xinjiang, China	16.3	
South Korea	14.61	Yoon, Seo <sup>22</sup>
Japan	17.3	AIST Research Center for CRM <sup>23</sup>

101 **Table S8. Time-activity factors used in this study**

Region/Country	Time spent in indoor (h/d)	Time spent in outdoor (h/d)	References
Beijing, China	20.75	3.25	
Tianjin, China	20.87	3.13	
Hebei, China	20.97	3.03	
Shanxi, China	20.25	3.75	
Inner Mongolia, China	19.83	4.17	
Liaoning, China	20.92	3.08	
Jilin, China	21.57	2.43	
Heilongjiang, China	20.5	3.5	
Shanghai, China	21.42	2.58	
Jiangsu, China	21.17	2.83	
Zhejiang, China	20.8	3.2	
Anhui, China	20.57	3.43	
Fujian, China	20.9	3.1	
Jiangxi, China	20.22	3.78	
Shandong, China	21.18	2.82	
Henan, China	19	5	Ministry of Environmental Protection <sup>21</sup>
Hubei, China	19.58	4.42	
Hunan, China	20.5	3.5	
Guangdong, China	20.5	3.5	
Guangxi, China	19.17	4.83	
Hainan, China	18.43	5.57	
Chongqing, China	20.55	3.45	
Sichuan, China	19.85	4.15	
Guizhou, China	20.18	3.82	
Yunnan, China	18.67	5.33	
Tibet, China	18.35	5.65	
Shaanxi, China	19.5	4.5	
Gansu, China	18.5	5.5	
Qinghai, China	21.18	2.82	
Ningxia, China	21.25	2.75	
Xinjiang, China	19.25	4.75	
South Korea	21.82	2.18	Yoon, Seo <sup>22</sup>
Japan	22.8	1.2	AIST Research Center for CRM <sup>23</sup>

103 **Table S9. Infiltration factors used in this study.**

Region/Country	Infiltration factors	References
Beijing, China	67.3%	
Tianjin, China	60.5%	
Hebei, China	57.5%	
Shanxi, China	56.8%	
Inner Mongolia, China	55.8%	
Liaoning, China	57.8%	
Jilin, China	56.3%	
Heilongjiang, China	57.5%	
Shanghai, China	81.5%	
Jiangsu, China	80.8%	
Zhejiang, China	82.5%	
Anhui, China	81.3%	
Fujian, China	84.8%	
Jiangxi, China	85.3%	
Shandong, China	63.5%	
Henan, China	62.8%	Zhang, Yun <sup>24</sup>
Hubei, China	81.5%	
Hunan, China	83.3%	
Guangdong, China	85.5%	
Guangxi, China	82.8%	
Hainan, China	88.0%	
Chongqing, China	84.0%	
Sichuan, China	82.8%	
Guizhou, China	81.3%	
Yunnan, China	82.0%	
Tibet, China	54.3%	
Shaanxi, China	58.5%	
Gansu, China	58.0%	
Qinghai, China	54.8%	
Ningxia, China	60.0%	
Xinjiang, China	54.5%	
South Korea	65.0%	Choi and Kang <sup>25</sup>
Japan	45.0%	Funasaka, Furuichi and Sakai <sup>26</sup>

104 Note that the infiltration factor for each province in China is computed by averaging the values of  
105 infiltration factors across heating/non-heating seasons and urban/rural areas for that province<sup>24</sup>.

106      **Table S10. Testing for the differences between production-based monthly population-weighted mean PM<sub>2.5</sub>**  
107      **concentration and consumption-based monthly population-weighted mean PM<sub>2.5</sub> concentration**

Year	Source	Receptor	Mean of production-based monthly population- weighted mean PM <sub>2.5</sub> concentration	Mean of consumption- based monthly population- weighted mean PM <sub>2.5</sub> concentration	t	p
2015	China	South Korea	8.75	6.73	13.57	< 0.001
2015	China	Japan	2.70	2.14	9.86	< 0.001
2015	South Korea	China	0.17	0.24	-2.31	0.041
2015	South Korea	Japan	0.44	0.31	9.85	< 0.001
2015	Japan	China	0.03	0.35	-9.62	< 0.001
2015	Japan	South Korea	0.22	0.38	-8.29	< 0.001
2015	Others	China	13.49	23.39	-7.53	< 0.001
2015	Others	South Korea	6.25	11.75	-14.38	< 0.001
2015	Others	Japan	4.38	6.01	-29.48	< 0.001
2017	China	South Korea	8.38	6.50	11.24	< 0.001
2017	China	Japan	2.64	2.14	10.74	< 0.001
2017	South Korea	China	0.07	0.16	-5.05	< 0.001
2017	South Korea	Japan	0.48	0.35	9.04	< 0.001
2017	Japan	China	0.01	0.27	-9.41	< 0.001
2017	Japan	South Korea	0.13	0.30	-10.65	< 0.001
2017	Others	China	12.34	20.70	-7.06	< 0.001
2017	Others	South Korea	5.68	10.19	-21.44	< 0.001
2017	Others	Japan	4.07	5.61	-27.58	< 0.001

108      Paired Student t-tests are used to test for the differences between production-based monthly population-weighted  
109      mean PM<sub>2.5</sub> concentrations (n=12) and consumption-based monthly population-weighted mean PM<sub>2.5</sub> concentrations  
110      (n=12). Note: PM<sub>2.5</sub>, fine particulate matter.

111      **Table S11. Testing for the differences between production-based monthly PM<sub>2.5</sub> population exposure and**  
 112      **consumption-based monthly PM<sub>2.5</sub> population exposure**

Year	Source	Receptor	Mean of production-based monthly PM <sub>2.5</sub> population exposure	Mean of consumption-based monthly PM <sub>2.5</sub> population exposure	t	p
2015	China	South Korea	3.80	2.92	13.57	< 0.001
2015	China	Japan	2.11	1.67	9.86	< 0.001
2015	South Korea	China	2.68	3.75	-2.25	0.046
2015	South Korea	Japan	0.34	0.24	9.85	< 0.001
2015	Japan	China	0.45	5.43	-9.65	< 0.001
2015	Japan	South Korea	0.10	0.17	-8.29	< 0.001
2015	Others	China	205.78	358.84	-7.73	< 0.001
2015	Others	South Korea	2.71	5.11	-14.38	< 0.001
2015	Others	Japan	3.42	4.70	-29.48	< 0.001
2017	China	South Korea	3.72	2.89	11.25	< 0.001
2017	China	Japan	2.06	1.67	10.72	< 0.001
2017	South Korea	China	1.10	2.62	-5.02	< 0.001
2017	South Korea	Japan	0.37	0.27	9.03	< 0.001
2017	Japan	China	0.13	4.23	-9.36	< 0.001
2017	Japan	South Korea	0.06	0.14	-10.65	< 0.001
2017	Others	China	191.13	323.61	-7.18	< 0.001
2017	Others	South Korea	2.53	4.53	-21.51	< 0.001
2017	Others	Japan	3.18	4.39	-27.64	< 0.001

113      Paired Student t-tests are used to test for the differences between production-based monthly PM<sub>2.5</sub> population  
 114      exposure (n=12) and consumption-based monthly PM<sub>2.5</sub> population exposure (n=12). Note: PM<sub>2.5</sub>, fine particulate  
 115      matter.

**Table S12. Contributions from source to receptor countries' nitrogen oxides (NOx) emissions in Northeast Asia in 2015.**

Year	Receptor country		China (Gg, %)		South Korea (Gg, %)		Japan (Gg, %)	
	Source country							
2015	Total NOx emissions of Receptor		24817.49	100%	1260.93	100%	2255.31	100%
	Responsibility allocation from a production perspective	China	24817.49	100%	0	0%	0	0%
		South Korea	0	0%	1260.93	100%	0	0%
		Japan	0	0%	0	0%	2255.31	100%
		Others	0	0%	0	0%	0	0%
	Responsibility allocation from a consumption perspective	China	19413.15	78.2%	118.72	9.4%	89.73	4.0%
		South Korea	150.68	0.6%	736.74	58.4%	14.9	0.7%
		Japan	340.57	1.4%	25.18	2.0%	1728.45	76.6%
		Others	4913.09	19.8%	380.29	30.2%	422.24	18.7%

Note: NOx, nitrogen oxides; Gg, Gigagram.

1      **Table S13. Studies of the source-receptor relationship of transboundary PM<sub>2.5</sub> pollution with South Korea as  
2      the receptor region for an analysis period equal or over one year.**

Entry	Year of anthropogenic emission inventory in China	Receptor	China' absolute contribution ( $\mu\text{g}/\text{m}^3$ )	China' relative contribution (%)
Han, Cai <sup>27</sup>	2017	South Korea	Not available (NA)	15.7%
Han, Cai <sup>27</sup>	2015	South Korea	NA	20.4%
Han, Cai <sup>27</sup>	2010	South Korea	NA	28.0%
Bae, Kim <sup>28</sup>	2010	Seoul, South Korea	14.15	42%
Bae, Kim <sup>29</sup>	2010	South Korea	10.08	56% <sup>a</sup>
National Institute of Environmental Research (NIER) <sup>30</sup>	2017	Seoul, Daejeon and Busan in South Korea	8.17 <sup>b</sup>	32.1%
Yim, Gu <sup>31</sup>	2010	South Korea	9.16	54.2%
This study	2015	South Korea	8.73	35.0%
This study	2017	South Korea	8.39	37.1%

3      Note: PM<sub>2.5</sub>, fine particulate matter; NA, not available; NIER, National Institute of Environmental Research;

4      a. Two estimations of China's relative contributions over South Korea are calculated using two different modelling  
5      grid resolutions.<sup>29</sup> The relative contribution of 56% is estimated using a higher modelling grid resolution and is  
6      believed to be more accurate.<sup>29</sup>

7      b. The contribution is estimated based data in Figure 2.7 in the report by National Institute of Environmental  
8      Research (NIER)<sup>30</sup> using the digitizer tool of OriginPro 2022.

10      **Table S14. Studies of the source-receptor relationship of transboundary PM<sub>2.5</sub> pollution with Japan as the  
11 receptor region for an analysis period equal or over one year.**

Entry	Year of anthropogenic emission inventory in China	Receptor	China' absolute contribution ( $\mu\text{g}/\text{m}^3$ )	China' relative contribution (%)
National Institute of Environmental Research (NIER) <sup>30</sup>	2017	Tokyo, Osaka, Fukuoka in Japan	2.85	24.6%
Yim, Gu <sup>31</sup>	2010	Japan	3.19	53.9%
Ikeda, Yamaji <sup>32</sup>	2008	Kyushu, Japan	5.45 <sup>a</sup>	61%
Ikeda, Yamaji <sup>32</sup>	2008	Chugoku, Japan	Not available (NA)	59%
Ikeda, Yamaji <sup>32</sup>	2008	Shikoku, Japan	NA	60%
Ikeda, Yamaji <sup>32</sup>	2008	Kinki, Japan	3.66 <sup>a</sup>	51%
Ikeda, Yamaji <sup>32</sup>	2008	Hokuriku, Japan	NA	55%
Ikeda, Yamaji <sup>32</sup>	2008	Tokai-Koshin, Japan	NA	45%
Ikeda, Yamaji <sup>32</sup>	2008	Tohoku, Japan	3.30 <sup>a</sup>	59%
Ikeda, Yamaji <sup>32</sup>	2008	Hokkaido, Japan	NA	69%
Ikeda, Yamaji <sup>32</sup>	2008	Kanto, Japan	2.44 <sup>a</sup>	39%
Ikeda, Yamaji <sup>33</sup>	2008	Fukue, Japan	14.13	78.5%
Ikeda, Yamaji <sup>33</sup>	2008	Oki, Japan	8.28	69%
Ikeda, Yamaji <sup>33</sup>	2008	Nonodake, Japan	5.30	46.1%
Ikeda, Yamaji <sup>33</sup>	2008	Rishiri, Japan	7.46	86.7%
This study	2015	Japan	2.71	22.1%
This study	2017	Japan	2.64	22.9%

12      Note: PM<sub>2.5</sub>, fine particulate matter; NA, not available; NIER, National Institute of Environmental Research;

13      a. The contribution is estimated based data in Figure 4 in the study by Ikeda, Yamaji<sup>32</sup> using the digitizer tool of  
14      OriginPro 2022.

15      **References**

- 16      1. Stettler MEJ, Eastham S, Barrett SRH. Air quality and public health impacts of UK airports. Part  
17      I: Emissions. *Atmospheric Environment* 2011; **45**(31): 5415-24. doi:10.1016/j.atmosenv.2011.07.012.
- 18      2. van der Werf GR, Randerson JT, Giglio L, et al. Global fire emissions estimates during 1997–  
19      2016. *Earth Syst Sci Data* 2017; **9**(2): 697-720. doi:10.5194/essd-9-697-2017.
- 20      3. Hudman RC, Moore NE, Mebust AK, et al. Steps towards a mechanistic model of global soil  
21      nitric oxide emissions: implementation and space based-constraints. *Atmos Chem Phys* 2012; **12**(16):  
22      7779-95. doi:10.5194/acp-12-7779-2012.
- 23      4. Murray LT, Jacob DJ, Logan JA, Hudman RC, Koshak WJ. Optimized regional and interannual  
24      variability of lightning in a global chemical transport model constrained by LIS/OTD satellite data.  
25      *Journal of Geophysical Research: Atmospheres* 2012; **117**(D20): D20307. doi:10.1029/2012JD017934.
- 26      5. Guenther AB, Jiang X, Heald CL, et al. The Model of Emissions of Gases and Aerosols from  
27      Nature version 2.1 (MEGAN2.1): an extended and updated framework for modeling biogenic  
28      emissions. *Geosci Model Dev* 2012; **5**(6): 1471-92. doi:10.5194/gmd-5-1471-2012.
- 29      6. Bouwman AF, Lee DS, Asman WAH, Dentener FJ, Van Der Hoek KW, Olivier JGJ. A global  
30      high-resolution emission inventory for ammonia. *Global Biogeochemical Cycles* 1997; **11**(4): 561-87.  
31      doi:10.1029/97GB02266.
- 32      7. Carn SA, Yang K, Prata AJ, Krotkov NA. Extending the long-term record of volcanic SO<sub>2</sub>  
33      emissions with the Ozone Mapping and Profiler Suite nadir mapper. *Geophysical Research Letters*  
34      2015; **42**(3): 925-32. doi:10.1002/2014GL062437.
- 35      8. Zender CS, Bian H, Newman D. Mineral Dust Entrainment and Deposition (DEAD) model:  
36      Description and 1990s dust climatology. *Journal of Geophysical Research: Atmospheres* 2003;  
37      **108**(D14). doi:10.1029/2002JD002775.
- 38      9. Philip S, Martin RV, Snider G, et al. Anthropogenic fugitive, combustion and industrial dust is a  
39      significant, underrepresented fine particulate matter source in global atmospheric models.  
40      *Environmental Research Letters* 2017; **12**(4): 044018. doi:10.1088/1748-9326/aa65a4.
- 41      10. Gong SL. A parameterization of sea-salt aerosol source function for sub- and super-micron  
42      particles. *Global Biogeochemical Cycles* 2003; **17**(4). doi:10.1029/2003GB002079.
- 43      11. Jaeglé L, Quinn PK, Bates TS, Alexander B, Lin JT. Global distribution of sea salt aerosols: new  
44      constraints from in situ and remote sensing observations. *Atmos Chem Phys* 2011; **11**(7): 3137-57.  
45      doi:10.5194/acp-11-3137-2011.
- 46      12. Riddick SN, Dragosits U, Blackall TD, Daunt F, Wanless S, Sutton MA. The global distribution  
47      of ammonia emissions from seabird colonies. *Atmospheric Environment* 2012; **55**: 319-27.  
48      doi:10.1016/j.atmosenv.2012.02.052.
- 49      13. Liang Q, Stolarski RS, Kawa SR, et al. Finding the missing stratospheric Bry: a global modeling  
50      study of CHBr<sub>3</sub> and CH<sub>2</sub>Br<sub>2</sub>. *Atmos Chem Phys* 2010; **10**(5): 2269-86. doi:10.5194/acp-10-2269-2010.
- 51      14. Ordóñez C, Lamarque JF, Tilmes S, et al. Bromine and iodine chemistry in a global chemistry-  
52      climate model: description and evaluation of very short-lived oceanic sources. *Atmos Chem Phys* 2012;  
53      **12**(3): 1423-47. doi:10.5194/acp-12-1423-2012.
- 54      15. Millet DB, Guenther A, Siegel DA, et al. Global atmospheric budget of acetaldehyde: 3-D model  
55      analysis and constraints from in-situ and satellite observations. *Atmos Chem Phys* 2010; **10**(7): 3405-  
56      25. doi:10.5194/acp-10-3405-2010.
- 57      16. Johnson MT. A numerical scheme to calculate temperature and salinity dependent air-water  
58      transfer velocities for any gas. *Ocean Sci* 2010; **6**(4): 913-32. doi:10.5194/os-6-913-2010.

- 59 17. Nightingale PD, Malin G, Law CS, et al. In situ evaluation of air-sea gas exchange  
60 parameterizations using novel conservative and volatile tracers. *Global Biogeochemical Cycles* 2000;  
61 **14**(1): 373-87. doi:10.1029/1999GB900091.
- 62 18. Vinken GCM, Boersma KF, Jacob DJ, Meijer EW. Accounting for non-linear chemistry of ship  
63 plumes in the GEOS-Chem global chemistry transport model. *Atmos Chem Phys* 2011; **11**(22): 11707-  
64 22. doi:10.5194/acp-11-11707-2011.
- 65 19. Holmes CD, Prather MJ, Vinken GCM. The climate impact of ship NOx emissions: an improved  
66 estimate accounting for plume chemistry. *Atmos Chem Phys* 2014; **14**(13): 6801-12. doi:10.5194/acp-  
67 14-6801-2014.
- 68 20. Sherwen T, Evans MJ, Carpenter LJ, et al. Iodine's impact on tropospheric oxidants: a global  
69 model study in GEOS-Chem. *Atmos Chem Phys* 2016; **16**(2): 1161-86. doi:10.5194/acp-16-1161-2016.
- 70 21. Ministry of Environmental Protection. Highlights of the Chinese exposure factors handbook  
71 (Adults). Beijing, China: China Environmental Science Press; 2014.
- 72 22. Yoon H, Seo J, Yoo S-K, et al. Updated general exposure factors for risk assessment in the  
73 Korean population. *Journal of Exposure Science & Environmental Epidemiology* 2022.  
74 doi:10.1038/s41370-022-00437-6.
- 75 23. AIST Research Center for CRM. Japanese Exposure Factors Handbook. National Institute of  
76 Advanced Industrial Science and Technology. 2007.  
[https://unit.aist.go.jp/riss/crm/exposurefactors/english\\_summary.html](https://unit.aist.go.jp/riss/crm/exposurefactors/english_summary.html).
- 77 24. Zhang W, Yun X, Meng W, et al. Urban residential energy switching in China between 1980 and  
78 2014 prevents 2.2 million premature deaths. *One Earth* 2021; **4**(11): 1602-13.  
80 doi:10.1016/j.oneear.2021.10.013.
- 81 25. Choi DH, Kang DH. Infiltration of Ambient PM2.5 through Building Envelope in Apartment  
82 Housing Units in Korea. *Aerosol and Air Quality Research* 2017; **17**(2): 598-607.  
83 doi:10.4209/aaqr.2016.06.0287.
- 84 26. Funasaka K, Furuichi Y, Sakai M. Intrusion of the atmospheric aerosol to indoor air by the  
85 difference in house structure and reference to measures approach from microchemical analysis. *Journal*  
86 *of the Housing Research Foundation "JUSOKEN"* 2018; **44**: 97-107.  
87 doi:10.20803/jusokenronbunjisen.44.0\_97.
- 88 27. Han X, Cai JZ, Zhang MG, Wang XF. Numerical simulation of interannual variation in  
89 transboundary contributions from Chinese emissions to PM2.5 mass burden in South Korea.  
90 *Atmospheric Environment* 2021; **256**: 118440. doi:10.1016/j.atmosenv.2021.118440.
- 91 28. Bae C, Kim BU, Kim HC, Yoo C, Kim S. Long-Range Transport Influence on Key Chemical  
92 Components of PM2.5 in the Seoul Metropolitan Area, South Korea, during the Years 2012-2016.  
93 *Atmosphere* 2020; **11**(1): 19. doi:10.3390/atmos11010048.
- 94 29. Bae M, Kim B-U, Kim HC, Kim S. A Multiscale Tiered Approach to Quantify Contributions: A  
95 Case Study of PM2.5 in South Korea During 2010–2017. *Atmosphere* 2020; **11**(2): 141.  
96 doi:10.3390/atmos11020141.
- 97 30. National Institute of Environmental Research (NIER). Summary Report of the 4th stage (2013–  
98 2017) LTP Project, 2019.  
[https://nier.go.kr/NIER/cmm/fms/NoLoginFileDown.do;jsessionid=C1A37B9309AC438907222958C0680EF9?atchFileId=FILE\\_00000000029154&fileSn=0](https://nier.go.kr/NIER/cmm/fms/NoLoginFileDown.do;jsessionid=C1A37B9309AC438907222958C0680EF9?atchFileId=FILE_00000000029154&fileSn=0)

- 101 31. Yim SHL, Gu YF, Shapiro M, Stephens B. Air quality and acid deposition impacts of local  
102 emissions and transboundary air pollution in Japan and South Korea. *Atmospheric Chemistry and*  
103 *Physics* 2019; **19**(20): 13309-23. doi:10.5194/acp-19-13309-2019.
- 104 32. Ikeda K, Yamaji K, Kanaya Y, et al. Source region attribution of PM2.5 mass concentrations over  
105 Japan. *Geochemical Journal* 2015; **49**(2): 185-94. doi:10.2343/geochemj.2.0344.
- 106 33. Ikeda K, Yamaji K, Kanaya Y, et al. Sensitivity analysis of source regions to PM2.5 concentration  
107 at Fukue Island, Japan. *J Air Waste Manage Assoc* 2014; **64**(4): 445-52.  
108 doi:10.1080/10962247.2013.845618.
- 109