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3 **Transboundary health impacts of transported global air pollution and**
4 **international trade**

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33 Millions die prematurely every year from disease caused by exposure to outdoor air
34 pollution¹⁻⁵. Some studies have estimated premature mortality related to local air
35 pollution sources⁶⁻⁷, but air quality and premature mortality can be affected by
36 atmospheric transport of pollution from distant sources⁸⁻¹⁸. Moreover, international
37 trade is contributing to the globalisation of emission and pollution as a result of the
38 production of goods (and their associated emissions) in one region, for consumption in
39 another region^{14,19-22}. The effects of international trade on air pollutant emissions²³, air
40 quality¹⁴, and health²⁴ have been investigated regionally, but a combined, global
41 assessment of the health impacts related to international trade and atmospheric air
42 pollution transport is lacking. Here we link four global models to estimate premature
43 mortality linked to fine particulate matter (PM_{2.5}) pollution as a result of atmospheric
44 transport and the production and consumption of goods and services in different world
45 regions. We find that, of 3.45 (2.38-4.14, 95% CI) million global premature deaths related
46 to PM_{2.5} pollution in 2007, about 12% or 411,100 (352,800-469,300, 95% CI) were related
47 to air pollutants emitted in a different region of the world, and about 22% or 762,400
48 (681,500-843,400, 95% CI) were associated with goods and services produced in one
49 region for consumption in another. For example, PM_{2.5} pollution produced in China in
50 2007 is linked to more than 64,800 (44,400-85,100, 95% CI) premature deaths in other
51 regions, including over 3,100 (1,800-4,200, 95% CI) premature deaths in Western Europe
52 and the U.S.; consumption in Western Europe and the U.S. is linked to over 108,600
53 (64,300-153,000, 95% CI) premature deaths in China. Our results reveal that
54 inter-regional health impacts associated with PM_{2.5} pollution as a result of international
55 trade are higher than those as a result of long-distance atmospheric pollutant transport.

56 Outdoor air pollution and its health impacts have typically been regarded as local or
57 regional problems with similarly local or regional solutions. In response to the health risk
58 caused by exposure to outdoor air pollution, many countries have adopted environmental laws
59 regulating major sources of outdoor air pollution such as industry, agriculture, and
60 transportation within their territories²⁵. However, it is also increasingly recognized that air
61 quality in a given location can be substantially affected by atmospheric transport of pollution
62 from distant sources, including sources on other continents⁸⁻¹⁴. This pollution transport

63 indicates that premature mortality related to air pollution is more than just a local issue^{12,15-18}.
64 Moreover, international trade is further globalizing the issue of air pollution mortality by
65 separating the locations where goods are consumed from the locations where the emission and
66 related pollution and mortality occur. Here, we link four state-of-the-art global models to
67 estimate for the first time the premature mortality of global PM_{2.5} (fine particulate matter with
68 diameter $\leq 2.5 \mu\text{m}$) air pollution related to not only the pollution physically produced in
69 different regions but also the pollution related to the goods and services that are ultimately
70 consumed in each region. Only the premature mortality of PM_{2.5} pollution is estimated in our
71 study given that prior studies have shown it accounts for over 90% of the global mortality
72 from outdoor air pollution^{1,5}.

73 Beginning with a newly developed emission inventory of primary air pollutants produced
74 in 13 world regions in 2007 (Extended Data Fig. 1), we use a multi-regional input-output
75 model of international trade to identify and isolate the emissions related to consumption and
76 investment in each region in that year. A detailed documentation of the methodology and data
77 used for developing the production- and consumption- based emission inventory is provided
78 in *Supplementary Information*. We then track the fractions of globally distributed PM_{2.5}
79 pollution contributed by emissions produced in each region and by emissions associated with
80 each region's consumption, using the chemical transport model GEOS-Chem²⁶. After that, we
81 followed the methods of the Global Burden of Disease (GBD) Study¹ to estimate the
82 premature mortality due to ambient PM_{2.5} exposure related to each region's production and
83 consumption, by applying the GEOS-Chem modeled regional fractional contributions to the
84 mortality calculated from the GDB2013 high-resolution ambient PM_{2.5} concentrations²⁷.
85 PM_{2.5}-related premature mortality linked to ischemic heart disease, stroke, lung cancer, and
86 chronic obstructive pulmonary disease is calculated by using an integrated exposure model²
87 that estimate the risk of premature mortality from each of the four diseases at different PM_{2.5}
88 exposure levels. Although errors propagated across multiple different global models may be
89 large, we have conducted extensive uncertainty analyses and made careful comparisons to
90 independent data^{12,13,18,27,28} in order to demonstrate the robustness of our main findings. A
91 detailed description of these models, their integration, their uncertainty, comparisons with
92 other studies, and a comprehensive listing of all data sources and key references is provided

93 in *Methods* and *Supplementary Information*.

94 We estimate that PM_{2.5}-related premature mortality in 2007 was 3.45 million (2.38-4.14
95 million, 95%CI; Extended data Table 1; *cf.* 3.22 million deaths in 2010 reported by the GBD¹
96 and 3.15 million in 2010 by Lelieveld et al.⁶). Of this total, we attribute 2.52 million deaths
97 (1.74-3.02, 95%CI) (attributable deaths, 73.0%) to production activities in specific regions.
98 The attributable production sectors include energy, industry, transportation, residential (both
99 fossil fuels and biofuels), and agriculture. The remaining deaths are related to emissions from
100 international shipping and aviation that are difficult to assign to specific regions, as well as
101 natural sources such as biogenic emissions, field burning, forest fires, and mineral dust that
102 are not directly related to consumption. Unless stated otherwise, the numbers of premature
103 deaths reported below and in the figures thus correspond only to the attributable deaths and do
104 not include those related to these unassigned emissions, and reflect median estimates rounded
105 to the nearest hundred.

106 Figure 1a-d show the spatial distribution of premature deaths due to PM_{2.5} air pollution
107 produced in China, Western Europe, the U.S., and India, respectively (see Extended Data Fig.
108 2a-i for analogous maps for other regions) in 2007. In each case, the largest health impacts of
109 pollution produced in a given region are local, but deaths in neighboring regions as well as in
110 more-distant areas are also evident due to intercontinental transport, particularly in downwind
111 areas with dense populations. Our results are broadly consistent with previous transboundary
112 studies^{12,13,18}, given the differences in various aspects of methodology (see details in
113 *Supplementary Information*).

114 Figure 2a shows the share of deaths in each region due to emissions in other regions. As
115 expected, hotspots of mortality impact from transboundary pollution occur in populous
116 neighboring regions. For example, 30,900 (14,100-47,700, 95%CI) deaths in the Rest of East
117 Asia region (which includes Japan and South Korea) were related to emissions in China (Fig.
118 1a and 2a), and 47,300 (20,300-74,400, 95%CI) deaths in Eastern Europe were related to
119 emissions in Western Europe (Fig. 1c and 2a). More distant impacts also occur: 2,300
120 (1,000-3,600, 95%CI) deaths in Western Europe are related to pollution transported from the
121 U.S. Globally, 16.3% (13.3-19.3%, 95%CI) of attributable deaths (or 12.0% (9.8-14.2%,
122 95%CI) of total deaths) were caused by pollution produced in a different region.

123 In addition to the physical transport of pollution in the atmosphere, international trade has
124 a powerful influence on the location of health impacts by allowing the production of
125 emissions to occur far from where goods and services are ultimately consumed. Figure 1
126 (right, e-h) shows the distribution of deaths due to PM_{2.5} pollution related to goods and
127 services consumed in representative regions in 2007 (see Extended Data Fig. 3a-i for
128 analogous maps for other regions). For each specific region, compared to the distribution of
129 deaths caused by production of emissions, consumption-based deaths are scattered more
130 widely around the world due to the impact of international trade (Fig. 1).

131 Figure 2b presented the share of deaths in each region due to consumption in other regions.
132 Regionally, the share of a region's deaths that are related to goods and services consumed
133 elsewhere varies from as little as 15.2% (14.2-16.3%, 95%CI) in the case of more-isolated,
134 less-developed regions like Sub-Saharan Africa to 53.7% (44.2-63.2%, 95%CI) in the case of
135 energy exporting regions like Russia (Fig. 2b). The inter-region health impacts through
136 international trade are much higher than through atmospheric transport. For example, 4.1%
137 (1.1-7.1%, 95%CI) of the total number of deaths in the U.S. are related to consumption in
138 Western Europe, while only 0.2% (0.1-0.4%, 95%CI) of deaths in the U.S. are related to
139 transboundary transport from Western Europe. Also noteworthy is the "spillover" effect in
140 neighboring regions; 34.3% (19.9-48.7%, 95%CI) of deaths in the Rest of East Asia is
141 attributable to the combined effects of pollution advection and international trade from China.
142 Globally, 30.2% (25.4-35.0%, 95%CI) of the attributable deaths (22.2% (18.7-25.7%, 95%CI)
143 of total deaths) were caused by pollution that was produced in a different region from where
144 the related goods and services were ultimately consumed.

145 International trade allows production and consumption activities to be physically separated,
146 with emissions occurring within the region where the goods are produced and related health
147 impacts concentrated within that producing region and nearby downwind regions, all of which
148 may be far from the region where those goods are ultimately consumed. Figure 3 shows the
149 net effect of international trade on emission, PM_{2.5} exposure, and mortality in each region, or
150 the difference between each of these parameters when assigned to the location where goods
151 and services were consumed rather than the location of production activities. Taking SO₂ (a
152 key precursor of secondary PM_{2.5}) as an example, Figure 3a shows the difference between

153 where SO₂ emissions were physically produced and where the related goods and services
154 were consumed, or the emissions “embodied” in the net trade of goods and services among
155 the 13 regions, in 2007. The world’s most developed regions such as the U.S., Western
156 Europe and Rest of East Asia are net embodied emission importers, which tend to import
157 goods and services from China as well as their less-developed neighboring areas and caused
158 pollution in the imported regions. China is the world’s largest embodied emission exporter,
159 with large quantities of SO₂ embodied in exports to the above three regions.

160 In turn, emissions displaced via trade are transported in the atmosphere, which then affects
161 population exposure to the pollution. Figure 3b shows the difference in global,
162 population-weighted mean concentrations of PM_{2.5} due to the emissions produced in each
163 region and the emissions related to the goods and services consumed in each region, or PM_{2.5}
164 exposure “embodied” in net trade. Although quite similar to the pattern of the emissions
165 embodied in trade (i.e. Fig. 3a), these changes in air quality highlight cases where there are
166 populous areas downwind of produced emissions. For example, emissions embodied in
167 Chinese exports have a disproportionately large effect on exposure in population-dense
168 regions (e.g., Japan and South Korea) that are near to and downwind of China (Fig. 3b and
169 Fig. 1).

170 Finally, Figure 3c shows the PM_{2.5}-related premature mortality embodied in net trade,
171 which incorporate the emissions displaced via trade, the subsequent changes in air quality as
172 pollution is transported in the atmosphere, and the health impacts of poor air quality. Given
173 China’s population density, high emissions-intensity, large proportion of exports, and the large
174 populations of neighboring regions, Chinese exports embody a greater number of deaths than
175 exports from any other region (Fig. 3c). In contrast, net imports to the U.S. and Western
176 Europe embody the greatest number of deaths (Fig. 3c).

177 Figure 4 summarizes the premature mortality due to both advection of PM_{2.5} air pollution
178 and displacement of pollution via international trade with a series of bar charts. The per capita
179 mortality is also presented in Extended Data Fig. 6 as an indicator of the emissions produced
180 per person in a country and the relative health impacts of those emissions (see details in
181 *Methods* section). Figure 4a shows that Chinese emissions cause more than twice the number
182 of deaths worldwide than the emissions of any other region, followed by emissions produced

183 in India and the Rest of Asia region. Perhaps surprisingly, Figure 4e shows that when these
184 deaths are allocated according to where the related goods and services are consumed, China
185 and India still dominate, which is consistent with the disproportionately local health impacts
186 of air pollution. However, the roles of Western Europe and the U.S. are also highlighted by
187 the consumption-based perspective (Fig. 4a and 4e).

188 Figure 4d shows the premature mortality in each region due to emissions produced in other
189 regions, revealing the substantial health impacts of extraterritorial pollution in the Rest of
190 Asia, India and Eastern Europe regions. When trade effects are also included, the
191 transboundary health impacts increase drastically, particularly in China and other emerging
192 markets (e.g., India and Russia), as well as in more-developed downwind regions, e.g. the
193 Rest of East Asia region (including Japan and South Korea) (Fig. 4h). In turn, consumption in
194 Western Europe, the U.S. and the Rest of Asia region correspond to the greatest number of
195 deaths in other regions (Fig. 4g).

196 Our findings quantify the extent to which air pollution is a global problem. In our global
197 economy, the goods and services consumed in one region may entail production of large
198 quantities of air pollution—and related mortality—in other regions. If the cost of imported
199 products is lower because of less stringent air pollution controls in the regions where they are
200 produced, then the consumer savings may come at the expense of lives lost elsewhere²⁹⁻³⁰.
201 Regional policies that regulate air quality by imposing a price on pollutant emissions may be
202 effective, and in some cases a considerable proportion of the overall costs of such policies
203 might be shared with consumers in other regions (*cf.* Fig. 3a). However, there is some
204 evidence that the polluting industries have tended to migrate to regions with more permissive
205 environmental regulations²⁹⁻³⁰, suggesting that there may be tension between a given region's
206 efforts to improve air quality and attract foreign direct investment. Improving pollution
207 control technologies in China, India and elsewhere in Asia would have a disproportionately
208 large health benefit in those regions and worldwide, and international cooperation to support
209 such pollution abatement efforts and reduce “leakage” of emission via international trade is in
210 the global interest.

211

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278

279 **Figure legends**

280 **Figure 1 | Worldwide premature mortality due to PM_{2.5} air pollution.** Maps show the number of
281 deaths related to either the air pollution produced (i.e. emitted) in (a-d) or pollution related to goods
282 and services consumed in (e-h) China, Western Europe, the U.S. and India. Differences of worldwide
283 premature mortality between production- and consumption-based PM_{2.5} air pollution for these four

284 regions are presented in Extended Data Fig. 4.

285

286 **Figure 2 | Shares of PM_{2.5}-related deaths in each region related to emissions produced or goods**
287 **and services consumed in other regions.** Each cell in the grid shows the fraction of deaths (%) that
288 occurred in the column region due to pollution produced in the row region (**a**) or goods and services
289 consumed in the row region (**b**). The diagonal thus reflects deaths in a region due to pollution produced
290 (**a**) or goods and services consumed (**b**) in that same region. In each case, total deaths in each region
291 are shown at the top, and the worldwide deaths caused by pollution produced (**a**) or consumption (**b**) in
292 each region are shown at the right. Uncertainty ranges of numbers in this figure are presented in
293 Extended Data Fig. 5.

294

295 **Figure 3 | Emissions, air quality changes, and premature mortality embodied in trade.** Maps show
296 differences between production- and consumption-based accounting of SO₂ emissions (**a**; Mt SO₂/yr),
297 population-weighted average PM_{2.5} exposure (**b**; µg/m³ PM_{2.5}), and premature mortality due to PM_{2.5}
298 air pollution (**c**; deaths). In each case, net importers are shown in red colors and net exporters in blue
299 colors. Although the emissions embodied in exports from regions like Latin America, Canada,
300 Sub-Saharan Africa and Australia are greater than the emissions embodied in their imports (blue
301 shading in **a**), the PM_{2.5} exposure and mortality embodied in imports to those regions are greater than
302 exposure and mortality embodied in their exports (red shading in **b** and **c**). The differences are due to
303 differences in population density (**b**) and marginal health impacts of emissions (**c**) in regions like China,
304 Europe, India and the Rest of Asia region (i.e. Central and Southeast Asia) which are the source of
305 many of the goods imported by other regions. The U.S., Western Europe, and the Rest of East Asia
306 region (South Korea and Japan) are net importers of pollution, exposure and deaths. Note that
307 Mongolia, North and South Korea and Japan are grouped in a single region (Rest of East Asia), which
308 tends to overemphasize the effect of trade in Mongolia in particular.

309

310 **Figure 4 | Summary of global premature mortality due to transported PM_{2.5} pollution and traded**
311 **products.** Worldwide mortality due to pollution produced (i.e. emitted) in each region (**a**), worldwide
312 mortality related to products consumed in each region (**e**), mortality in region due to pollution produced
313 in that region (**b**), mortality in region related to products consumed in that region (**f**), mortality in other
314 regions due to pollution produced in each region (**c**), mortality in other regions related to products
315 consumed in each region (**g**), mortality in each region due to pollution produced elsewhere (**d**), and
316 mortality in each region related to products consumed elsewhere (**h**). Error bars in each panel presented
317 uncertainty ranges (95%CI) of the estimates, which are determined by uncertainties in GEOS-Chem
318 simulated fractional contribution of PM_{2.5} exposure and in total PM_{2.5} related mortality.

319

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329

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331 D.G.S. provided emission data. M.B., A.V.D., and R.V.M. provided PM_{2.5} exposure data. D.T.,
332 H.Z., T.F., and D.G. calculated emissions. G.G. conducted GEOS-Chem simulations. X.J.
333 conducted health impacts estimates. Q.Z., X.J., S.J.D., G.G., and J.L. interpreted the data. Q.Z.,
334 X.J., D.T., S.J.D., H.Z., and G.G. wrote the paper with inputs from all co-authors.

335

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342

343 **Methods**

344 **Integrated model framework**

345 This study required integration of data, models and methods from multiple sources and
346 scientific disciplines, as depicted in Extended Data Fig. 7. We first developed a global
347 inventory of all major sources of anthropogenic air pollution emissions in 228 countries and
348 regions for the year 2007, disaggregating emissions from 62 sub-sectors (as opposed to
349 aggregated sectors in available global inventories). We then used a global multi-regional
350 input-output model (MRIO)^{31,32} based on data from the Global Trade Analysis Project
351 (GTAP)³³ to re-attribute the emissions produced by these different sectors according to the
352 demand of consumers for finished goods. The MRIO thus traces all emissions related to
353 consumed goods back to the original sources of produced emissions, even if the supply chain
354 of the consumed products encompasses intermediate inputs (e.g., parts) and services (e.g.,
355 assembly and transport) from multiple sectors across multiple regions. Prior to the
356 re-attribution, the production-based global emission inventory was mapped to 129 regions and
357 57 sectors in GTAP to facilitate the MRIO analysis. Next, we used the GEOS-Chem chemical
358 transport model²⁶ to track physical transport of emissions in the atmosphere, obtaining each
359 region's fractional contribution to global near-surface PM_{2.5} concentrations from both
360 production and consumption perspectives by a zero-out approach. These derived ratios were

361 further multiplied by high-resolution global PM_{2.5} concentration data²⁷ developed for the
362 Global Burden of Disease Study of 2013 (GBD2013) to get the PM_{2.5} exposure levels from
363 both production and consumption perspectives. Given computational constraints, the
364 GEOS-Chem modeling required further geographical aggregation: we classified the world
365 into 13 regions based on their level of economic development, regions in the trade model, and
366 levels of air pollution: China, Rest of East Asia, India, Rest of Asia, Russia, Western Europe,
367 Eastern Europe, Middle East and North Africa, the U.S, Canada, Latin America, Sub-Saharan
368 Africa, and Rest of World. The detailed classifications from 228 countries sorted into these 13
369 regions are shown in Supplementary Table 1 and Extended Data Fig. 1. Finally, we applied
370 the Integrated Exposure-Response (IER) model² to evaluate the effect of changes in PM_{2.5}
371 concentrations to premature mortality, summing across regions to obtain the global PM_{2.5}
372 mortality related to both emissions produced and goods consumed in each region. Detailed
373 information of all above steps is presented in the *Supplementary Information*.

374 We conducted comprehensive uncertainty analyses integrating errors in all steps, and
375 compared our results with independent data. In summary, we estimate uncertainty (p=0.005)
376 associated with production-based emissions using distributions of key parameters derived
377 from the literature, expert judgments and measurement data for each industrial subsector in
378 each of the 13 regions. Our estimates are generally consistent with the HTAP v2.2 emission
379 inventory²⁸ that represents the state-of-the-art understanding of global emissions. We also
380 evaluate uncertainty related to our modeling of atmospheric transport (including, e.g.,
381 sensitivity analyses of nonlinear effects and neglected NMVOC emissions), and compare our
382 results to both ground-based observations and GBD PM_{2.5} concentrations. Our results on
383 transboundary transport of PM_{2.5} are generally consistent with the HTAP study¹³ when
384 harmonizing the model domain and target species. And we assess uncertainties of our
385 mortality estimates by varying the applicable parameters in our Integrated
386 Exposure-Response model across 1,000 trials and our estimates of mortality are very close to
387 the GBD¹ and Lelieveld et al.⁶. Details of these analyses are presented in the *Supplementary*
388 *Information*.

389

390 **Per capita mortality due to transported pollution and traded products**

391 Extended Data Figure 6a shows that the emissions produced by a million Eastern
392 Europeans result in 1,027 (749-1,306, 95%CI) PM_{2.5}-related deaths around the world, a
393 greater impact per capita than any other region. Having the world's largest population, per
394 capita impacts in China are quite substantial: the emissions produced per million Chinese
395 cause 770 (529-1,014, 95%CI) deaths worldwide (Extended Data Fig. 6a). In terms of
396 consumption, individuals in the affluent regions, e.g., Western Europe, the U.S., and Canada,
397 are related to greater than average number of deaths worldwide (Extended Data Fig. 6e).
398 Further, a disproportionate number of those deaths occurred in other regions; every million
399 Western European, Canadian and U.S. consumers were tied to 416 (303-530, 95%CI), 395

400 (268-522, 95%CI), and 339 (231-448, 95%CI) deaths in other regions, respectively (Extended
401 Data Fig. 6g). Per capita, Eastern Europe and Russia suffered more of these transboundary
402 deaths than any other regions: per million people in those regions, 531 (335-727, 95%CI) and
403 365 (278-453, 95%CI) died, respectively, due to products consumed elsewhere (Extended
404 Data Fig. 6h).

405

406 **References**

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413

414 **Data availability statement** The datasets generated during the current study are available
415 from the corresponding author on reasonable request.

416

417 **Extended Data Legends**

418 **Extended Data Figure 1 | Definition of 13 world regions in this study.**

419

420 **Extended Data Figure 2 | Global distribution of premature mortality related to production-based**
421 **PM_{2.5} air pollution.** Maps show the number of deaths related to air pollution produced (i.e., emitted) in
422 (a) Rest of East Asia, (b) Rest of Asia, (c) Russia, (d) Eastern Europe, (e) Canada, (f) Middle East and
423 North Africa, (g) Latin America, (h) Sub-Saharan Africa, and (i) Rest of the world.

424

425 **Extended Data Figure 3 | Global distribution of premature mortality related to**
426 **consumption-based PM_{2.5} air pollution.** Maps show the number of deaths related to goods and
427 services consumed in (a) Rest of East Asia, (b) Rest of Asia, (c) Russia, (d) Eastern Europe, (e) Canada,
428 (f) Middle East and North Africa, (g) Latin America, (h) Sub-Saharan Africa, and (i) Rest of the world.

429

430 **Extended Data Figure 4 | Differences of worldwide premature mortality between production- and**
431 **consumption-based PM_{2.5} air pollution (consumption-based minus production-based).**

432

433 **Extended Data Figure 5 | Uncertainty ranges of Figure 2.** The top and the right represent the 95%
434 CI ranges of total number of death. Each cell in the grid shows the standard derivation of the fraction of
435 deaths (%)

436

437 **Extended Data Figure 6 | Summary of global premature mortality per capita of population due to**

438 **transported pollution and traded products.** Worldwide mortality due to pollution produced (i.e.
439 emitted) in each region (a), worldwide mortality related to products consumed in each region (e),
440 mortality in region due to pollution produced in that region (b), mortality in region related to products
441 consumed in that region (f), mortality in other regions due to pollution produced in each region (c),
442 deaths in other regions related to products consumed in each region (g), mortality in each region due to
443 pollution produced elsewhere (d), and mortality in each region related to products consumed elsewhere
444 (h). Data are normalized according to regional population.

445

446 **Extended Data Figure 7 | Methodology framework to access PM_{2.5} mortality from each region'**
447 **production and consumption.**

448

449 **Extended Data Table 1 | Premature mortality related to PM_{2.5} air pollution in 2007.**