

Transboundary health impacts of transported global air pollution and international trade

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Millions of people die every year from diseases caused by exposure to outdoor air pollution^{1–3}. Some studies have estimated premature mortality related to local sources of air pollution^{4,5}, but local air quality can also be affected by atmospheric transport of pollution from distant sources^{6–18}. International trade is contributing to the globalization of emission and pollution as a result of the production of goods (and their associated emissions) in one region for consumption in another region^{14,19–21}. The effects of international trade on air pollutant emissions²², air quality²⁴ and health²⁴ have been investigated regionally, but a combined, global assessment of the health impacts related to international trade and the transport of atmospheric air pollution is lacking. Here we combine four global models to estimate premature mortality caused by fine particulate matter (PM_{2.5}) pollution as a result of atmospheric transport and the production and consumption of goods and services in different world regions. We find that, of the 3.45 million premature deaths related to PM_{2.5} pollution in 2007 worldwide, about 12 per cent (411,100 deaths) were related to air pollutants emitted in a region of the world other than that in which the death occurred, and about 22 per cent (762,400 deaths) were associated with goods and services produced in one region for consumption in another. For example, PM_{2.5} pollution produced in China in 2007 is linked to more than 64,800 premature deaths in regions other than China, including more than 3,100 premature deaths in western Europe and the USA; on the other hand, consumption in western Europe and the USA is linked to more than 108,600 premature deaths in China. Our results reveal that the transboundary health impacts of PM_{2.5} pollution associated with international trade are greater than those associated with long-distance atmospheric pollutant transport.

Outdoor air pollution and the associated effects on health have typically been regarded as local or regional problems, with local or regional solutions. In response to the health risk caused by exposure to outdoor air pollution, many countries have adopted environmental policies to regulate major sources of outdoor air pollution such as industry, agriculture and transportation within their territories²⁵. However, it is also increasingly recognized that air quality in a given location can be substantially affected by atmospheric transport of pollution from distant sources, including sources on other continents^{6–14}. This transport of pollution indicates that premature mortality related to air pollution (that is, death of an individual before his or her life expectancy due to exposure to air pollution) is not only a local issue^{14,19–21}. International trade is further globalizing the issue of

air-pollution-related mortality by separating the locations where goods are consumed from the locations where the emissions and related pollution and mortality occur. Here we combine four state-of-the-art global models to estimate the premature mortality linked to global PM_{2.5} (fine particulate matter with an aerodynamic diameter of 2.5 µm or less) air pollution; we attribute the global premature deaths not only to the pollution physically produced within the different regions, but also to pollution related to goods and services that are ultimately consumed in each region. We estimate premature mortality resulting from only PM_{2.5} pollution because previous studies have shown that this type of pollution accounts for more than 90% of the global mortality from outdoor air pollution¹⁴.

Beginning with a newly developed emissions inventory of primary air pollutants produced in 13 world regions in 2007 (Extended Data Fig. 1), we use a multi-regional input–output model of international trade to identify and isolate the emissions related to consumption and investment in each region in that year. (The methodology and data used for developing the production- and consumption-related emissions inventory is provided in Supplementary Information.) We then track the globally distributed PM_{2.5} pollution that is contributed by emissions produced in each region and by emissions associated with consumption in each region using the chemical transport model GEOS-Chem²⁶. Next, following the methods of the Global Burden of Disease (GBD) Study²⁷, we estimate the premature mortality due to exposure to outdoor PM_{2.5} related to production and consumption in each region; we apply the GEOS-Chem-modelled regional fractional contributions to mortality calculated using the high-resolution PM_{2.5} concentrations from the GBD Study of 2013²⁷. PM_{2.5}-related premature mortality linked to ischaemic heart disease, stroke, lung cancer and chronic obstructive pulmonary disease is calculated by using an integrated exposure model² that estimates the risk of premature mortality from each of the four diseases at different levels of exposure to PM_{2.5}. Because errors propagated across multiple global models can be large, we conducted uncertainty analyses and made comparisons with independent data^{14,18,19,27,28} to demonstrate the robustness of our main findings. A description of these models, their integration and uncertainty, comparisons with other studies, and a comprehensive listing of all data sources and key references are provided in Methods and Supplementary Information.

We estimate that PM_{2.5}-related premature mortality in 2007 was 3.45 million (95% confidence interval (CI), 2.38–4.14 million; Extended Data Table 1; compare with 3.22 million deaths in 2010 reported by

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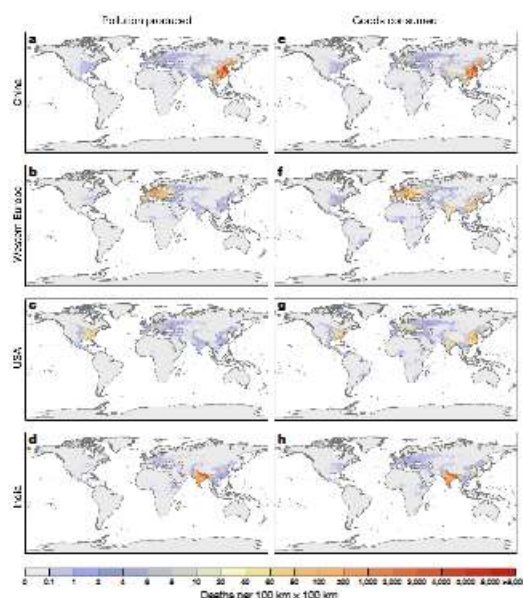


Figure 1 | Worldwide premature mortality in 2007 due to $PM_{2.5}$ air pollution. a–h. Maps show the number of deaths related to either the air pollution produced (that is, emitted) in the given region (a, China; b, western Europe; c, USA; d, India) or the air pollution related to goods

and services consumed in that region (e–h). Differences in worldwide premature mortality between production- and consumption-related $PM_{2.5}$ air pollution for these four regions are presented in Extended Data Fig. 4.

the GBD Study³ and 3.15 million in 2010 by Lelieveld et al.⁶). Of this total, we attribute 2.52 million deaths (73.0%, 95% CI, 1.74–3.02 million deaths) to production activities in specific regions. The related production sectors include energy, industry, transportation, residential (both fossil fuels and biofuels) and agriculture. The remaining deaths are related to emissions from international shipping and aviation, which are difficult to assign to specific regions, or to emissions from natural sources such as biogenic emissions, field burning, forest fires and mineral dust, which are not directly related to consumption. Unless stated otherwise, the numbers of premature deaths reported hereafter correspond to only the deaths attributable to emissions from an identifiable production sector in a specific region ('attributable deaths') and do not include those related to the aforementioned unassignable or non-consumption-related emissions, and reflect median estimates rounded to the nearest hundred.

Figure 1a–d shows the global spatial distribution of premature deaths in 2007 due to $PM_{2.5}$ air pollution produced in China, western Europe, the USA and India, respectively (see Extended Data Fig. 2a–i for maps for other regions). In each case, the greatest health impacts of pollution produced in a given region are local, but deaths in neighbouring and more distant regions are also evident, owing to intercontinental transport, particularly in downwind areas with dense populations. Our results are broadly consistent with previous transboundary pollution studies^{12,13,14}, given the differences in methodology (Supplementary Information).

Figure 2a shows the percentage of deaths in each region due to emissions in that and other regions. As expected, hotspots of mortality due to transboundary pollution occur in populous neighbouring regions. For example, 30,900 (95% CI, 14,100–47,700) deaths in the 'rest of east Asia' region (which includes Japan and South Korea) were related to emissions in China (Figs 1a, 2a) and 47,300 (95% CI, 20,300–74,400) deaths in eastern Europe were related to emissions in western Europe (Figs 1c, 2a). More distant effects are also evident: for example, 2,300 (95% CI, 1,000–3,600) deaths in western Europe were related to pollution transported from the USA. Globally, 16.3% (95% CI, 13.3%–19.3%) of the attributable deaths, or 12.0% (95% CI, 9.8%–14.2%) of total $PM_{2.5}$ -related deaths, were caused by pollution produced in a region other than that in which the death occurred.

In addition to the physical transport of pollution in the atmosphere, international trade has an influence on the regions where health impacts are greatest by allowing the production of emissions to occur far from where goods and services are ultimately consumed. Figure 1e–h shows the distribution of deaths in 2007 due to $PM_{2.5}$ pollution related to goods and services consumed in the representative regions (see Extended Data Fig. 3a–i for maps for other regions). For each region, compared to the distribution of deaths attributable to the direct production of emissions, consumption-related deaths are scattered more widely around the world owing to international trade (Fig. 1).

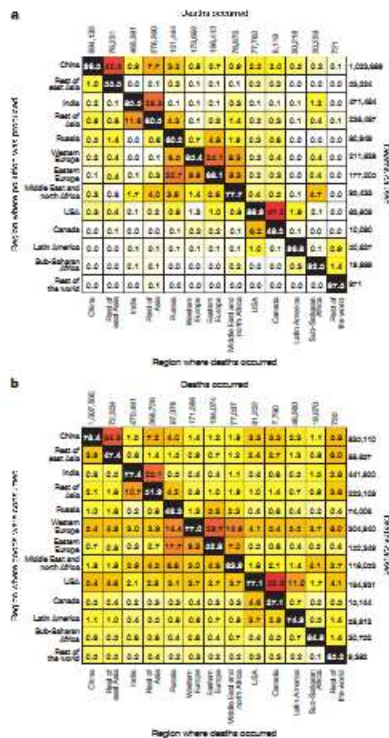


Figure 2 | Proportion of $PM_{2.5}$ -related deaths in a given region that are linked to emissions produced or goods and services consumed in that and other regions. **a**, **b**. Each cell in the grid shows the fraction of deaths (%) that occurred in the region indicated by the column due to pollution produced (**a**) or due to goods and services consumed (**b**) in the region indicated by the row. The diagonal thus reflects deaths in a region due to pollution produced (**a**) or goods and services consumed (**b**) in that same region. Darker shading in the off-diagonal cells highlights higher fractions. In each case, the number of attributable deaths that occurred in each region is shown at the top, and the number of worldwide deaths caused directly by pollution produced in each region (**a**) or indirectly by consumption of products in each region that are produced in that region or elsewhere (**b**) is shown at the right. Uncertainty ranges for the numbers given here are presented in Extended Data Fig. 5. The regions are defined in Extended Data Fig. 1.

Figure 2b shows the percentage of deaths in each region due to emissions related to consumption in that and other regions. Regionally, the share of deaths in a given region that are related to goods and services consumed elsewhere varies from 15.2% (95% CI, 14.2%–16.3%) in the more-isolated, less-developed region of sub-Saharan Africa to 53.7%

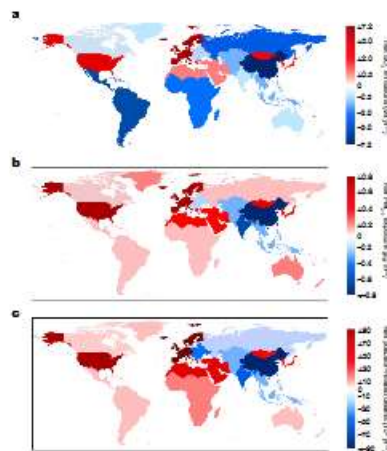


Figure 3 | Emissions, changes in air quality and premature mortality embodied in trade. **a–c**. Maps show differences between production- and consumption-based accounting of SO_2 emissions (**a**), in units of megatonnes of SO_2 per year, population-weighted average $PM_{2.5}$ exposure (**b**), in units of micrograms of $PM_{2.5}$ per cubic metre, or premature mortality due to $PM_{2.5}$ air pollution (**c**, deaths per year). In each case, net importers are shown in shades of red and net exporters in shades of blue. Although the emissions embodied in exports from regions such as Latin America, Canada, sub-Saharan Africa and Australia are greater than the emissions embodied in their imports (blue shading in **a**), the $PM_{2.5}$ exposure and mortality embodied in imports to those regions are greater than the exposure and mortality embodied in their exports (red shading in **b** and **c**). The differences are due to differences in population density (**b**) and the marginal health impacts of emissions (**c**) in regions such as China, Europe, India and the 'rest of Asia' region (that is, central and southeast Asia), which are the source of many of the goods imported by other regions. The USA, western Europe and the 'rest of east Asia' region (including South Korea and Japan) are net importers of pollution, exposure and deaths. Note that Mongolia, North Korea, South Korea and Japan are grouped into a single region ('rest of east Asia'), which tends to overemphasize the effect of trade, in Mongolia in particular.

(95% CI, 44.2%–63.2%) in the high-energy-exporting region of Russia (Fig. 2b). The transboundary health impacts related to international trade are much greater than those related to atmospheric transport. For example, 4.1% (95% CI, 1.1%–7.1%) of the attributable deaths in the USA are related to consumption in western Europe, whereas only 0.2% (95% CI, 0.1%–0.4%) are related to transboundary transport of pollution from western Europe. The 'spillover' effect in neighbouring regions is also noteworthy: 34.3% (95% CI, 19.9%–48.7%) of deaths in the 'rest of east Asia' region are attributable to the combined effects of the advection of pollution and international trade from China. Globally, 30.2% (95% CI, 25.4%–35.0%) of the attributable deaths, or 22.2% (95% CI, 18.7%–25.7%) of total $PM_{2.5}$ -related deaths, were caused by pollution produced in a region other than that in which the related goods and services were ultimately consumed.

International trade allows production and consumption activities to be physically separated, with emissions occurring within the region where the goods are produced and related health impacts concentrated

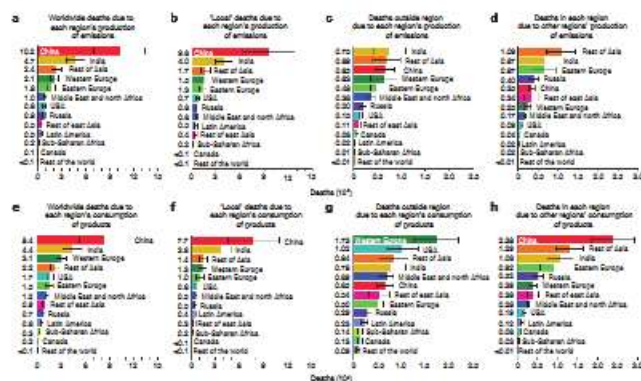


Figure 4 | Summary of global premature mortality due to transported $PM_{2.5}$ pollution and traded products. **a, e**, Worldwide mortality due to pollution produced (that is, emitted) in each region (**a**) or related to products consumed in each region (**e**). **b, f**, Mortality in each region due to pollution produced in that region (**b**) or related to products consumed in that region (**f**). **c, g**, Mortality in all other regions due to pollution produced in each region (**c**) or related to products consumed in each region (**g**). Note that the number of deaths in each region in **b** and

c (and **g**) therefore sum to those in the same region in **a** (**e**). **d, h**, Mortality in each region due to pollution produced elsewhere (**d**) or related to products consumed elsewhere (**h**). The numbers denote the left-hand side of each panel give the number of deaths in 2007 (in units of 10^3). Error bars denote 95% CI, determined by uncertainties in the GEOS-Chem-simulated fractional contribution of $PM_{2.5}$ exposure and in the total $PM_{2.5}$ -related mortality.

within that producing region and nearby downwind regions, all of which might be far from the regions where those goods are ultimately consumed. Figure 3 shows the net effect of international trade on emissions, $PM_{2.5}$ exposure and mortality in each region, quantified, for each parameter, as the difference between its value when assigned according to the region where goods and services were consumed and when assigned according to the location of production. Taking SO_2 (a key precursor of secondary $PM_{2.5}$) as an example, Fig. 3a shows the difference between where SO_2 emissions were physically produced and where the related goods and services were consumed, thereby highlighting the emissions embodied in the net trade of goods and services among the 13 regions, in 2007. The most developed regions of the world, such as the USA, western Europe and the 'rest of east Asia' region, are importers of net embodied emissions: they tend to import goods and services from China and less-developed neighbouring areas, thereby causing pollution in those regions. China is the world's largest exporter of embodied emissions, with large quantities of SO_2 embodied in exports to the aforementioned three regions.

In turn, emissions displaced via trade are transported in the atmosphere, which then affects population exposure to the pollution. Figure 3b shows the difference between global, population-weighted mean concentrations of $PM_{2.5}$ due to the emissions produced in each region and those due to the emissions related to the goods and services consumed in each region—that is, the $PM_{2.5}$ exposure that is embodied in net trade. Although similar to the pattern of the emissions embodied in trade (Fig. 3a), these changes in air quality highlight cases for which there are populous areas downwind of where the emissions are produced. For example, emissions embodied in Chinese exports have a disproportionately large effect on exposure in population-dense regions (for example, Japan and South Korea) that are near to and downwind of China (Figs 1, 3b).

Finally, Fig. 3c shows the $PM_{2.5}$ -related premature mortality embodied in net trade, which incorporates the emissions displaced via trade, the subsequent changes in air quality as pollution is transported

in the atmosphere, and the health impacts of poor air quality. Given China's population density, high emission intensity, large proportion of exports, and the large populations of neighbouring regions, Chinese exports embody a greater number of deaths than do exports from any other region (Fig. 3c). By contrast, net imports to the USA and western Europe embody the greatest number of deaths (Fig. 3c).

Figure 4 summarizes premature mortality due to both advection of $PM_{2.5}$ air pollution and displacement of pollution via international trade with a series of bar charts. The per-capita mortality is presented in Extended Data Fig. 6 as an indicator of the emissions produced per person in a country and the relative health impacts of those emissions (see details in Methods). Figure 4a shows that emissions produced in China cause more than twice the number of deaths worldwide than do the emissions produced in any other region, followed by emissions produced in India and the 'rest of Asia' region. Figure 4e shows that when these deaths are allocated according to where the related goods and services are consumed, China and India still dominate, consistent with the health impacts of air pollution being mostly local; however, the roles of western Europe and the USA are also highlighted by the consumption-based perspective (Fig. 4a, e).

Figure 4d shows the premature mortality in each region due to emissions produced in other regions, revealing the substantial health impacts of transboundary pollution in the 'rest of east Asia' region, India and eastern Europe. When trade effects are also included, the transboundary health impacts increase markedly, particularly in China and other emerging markets (for example, India and Russia), and in more-developed downwind regions (for example, the 'rest of east Asia' region, which includes Japan and South Korea) (Fig. 4h). In turn, consumption in western Europe, the USA and the 'rest of Asia' region corresponds to the greatest number of deaths in other regions (Fig. 4g).

Our findings quantify the extent to which air pollution is a global problem. In our global economy, the goods and services consumed in one region may entail production of large quantities of air pollution—and related mortality—in other regions. If the cost of imported

products is lower because of less stringent air pollution controls in the regions where they are produced, then the consumer savings may come at the expense of lives lost elsewhere^{29,30}. Regional policies that regulate air quality by imposing a price on pollutant emissions may be effective, and in some cases a considerable proportion of the overall costs of such policies might be shared with consumers in other regions (see Fig. 3a). However, there is some evidence that the polluting industries have tended to migrate to regions with more permissive environmental regulations^{31,32}, suggesting that there may be tension between efforts to improve air quality in a given region and to attract direct foreign investment. Improving pollution control technologies in China, India and elsewhere in Asia would have a disproportionately large health benefit in those regions and worldwide, and international cooperation to support such pollution abatement efforts and to reduce 'leakage' of emission via international trade is in the global interest.

Online Content Methods, along with any additional Extended Data display items and Source Data, are available in the online version of the paper; references unique to these sections appear only in the online paper.

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Supplementary Information is available in the online version of the paper.

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Author Contributions Q.Z., J.L. and K.H. conceived the study. Q.Z. led the study; Z.L. and D.G.S. provided emissions data. M.B., A.V.D. and R.V.M. provided PM_{2.5} exposure data. D.T., H.Z., T.F. and D.G. calculated emissions. G.G. conducted GEOS-Chem simulations. X.J. conducted estimates of health impacts. Q.Z., X.J., S.J.D., G.G. and J.L. interpreted the data. Q.Z., X.J., D.T., S.J.D., H.Z. and G.G. wrote the paper with input from all co-authors.

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METHODS

Integrated model framework. This study required integration of data, models and methods from multiple sources and scientific disciplines, as depicted in Extended Data Fig. 7. We first developed a global inventory of all major sources of anthropogenic air pollution emissions in 228 countries and regions for the year 2007, disaggregating emissions from 62 subsectors (as opposed to aggregated sectors in available global inventories). We then used a global multi-regional input-output model (MRIO)^{31,32} based on data from the Global Trade Analysis Project (GTAP)³³ to re-attribute the emissions produced by these different sectors according to the demand of consumers for finished goods. The MRIO thus traces all emissions related to consumed goods back to the original sources of produced emissions, even if the supply chain of the consumed products encompasses intermediate inputs (for example, parts) and services (for example, assembly and transport) from multiple sectors across multiple regions. Prior to the re-attribution, the production-based global emission inventory was mapped to 129 regions and 57 sectors in GTAP to facilitate the MRIO analysis. Next, we used the GEOS-Chem chemical transport model³⁴ to track physical transport of emissions in the atmosphere, obtaining the fractional contribution of each region to global near-surface PM_{2.5} concentrations from both production and consumption perspectives by a zero-out approach. These derived ratios were multiplied by high-resolution global PM_{2.5} concentration data³⁵ developed for the Global Burden of Disease Study of 2013 (GBD2013) to obtain the PM_{2.5} exposure levels from both production and consumption perspectives. Given the computational constraints of the chemical transport model, the GEOS-Chem modelling required further geographical aggregation. We classified the world into 13 regions on the basis of their level of economic development, regions in the trade model and levels of air pollution: China, rest of east Asia, India, rest of Asia, Russia, western Europe, eastern Europe, Middle East and north Africa, USA, Canada, Latin America, sub-Saharan Africa and rest of the world. The classifications used to sort the 228 countries into these 13 regions are shown in Supplementary Table 1 and Extended Data Fig. 1. Finally, we applied the Integrated Exposure-Response (IER) model⁶ to evaluate the effect of changes in PM_{2.5} concentrations to premature mortality, summing across regions to obtain the global PM_{2.5} mortality related to both emissions produced and goods consumed in each region. See Supplementary Information for further details of all of the above steps.

We conducted comprehensive uncertainty analyses, integrating errors in all steps, and compared our results with independent data. In summary, we estimate uncertainty ($P = 0.005$) associated with production-based emissions using distributions of key parameters derived from the literature, expert judgments and measurement data for each industrial subsector in each of the 13 regions. Our estimates are generally consistent with the HTAP v2.2 emission inventory²¹,

which represents the state-of-the-art understanding of global emissions. We also evaluated uncertainty related to our modelling of atmospheric transport (including sensitivity analyses of nonlinear effects and neglected emissions of non-methane volatile organic compounds) and compared our results to both ground-based observations and GBD PM_{2.5} concentrations. Our results on transboundary transport of PM_{2.5} are generally consistent with the HTAP study²¹ when harmonizing the model domain and target species. We assessed the uncertainties of our mortality estimates by varying the applicable parameters in our IER model across 1,000 trials; our estimates of mortality are very close to those from the GBD Study⁶ and by Lelieveld *et al.*⁴. Details of these analyses are presented in Supplementary Information.

Per-capita mortality due to transported pollution and traded products. Extended Data Fig. 6a shows that the emissions produced per one million people in eastern Europe result in 1,027 (95% CI, 749–1,306) PM_{2.5}-related deaths around the world—a greater impact per capita than any other region. Having the world's largest population, per-capita impacts in China are quite substantial: the emissions produced per one million people in China cause 770 (95% CI, 529–1,014) deaths worldwide (Extended Data Fig. 6a). In terms of consumption, consumers in affluent regions such as western Europe, the USA and Canada are associated with a greater-than-average number of PM_{2.5}-related deaths worldwide (Extended Data Fig. 6a). Further, a disproportionate number of those deaths occurred in regions other than that in which the products were consumed: for every one million consumers in western Europe, Canada and the USA, 416 (95% CI, 308–530), 395 (95% CI, 268–522) and 339 (95% CI, 231–448) PM_{2.5}-related deaths, respectively, occurred in other regions (Extended Data Fig. 6a). Per capita, eastern Europe and Russia suffered more of these transboundary deaths than did any other region: per one million people in those regions, 531 (95% CI, 335–727) and 565 (95% CI, 273–853) died, respectively, as a result of products consumed elsewhere (Extended Data Fig. 6a).

Data availability. The datasets generated during this study are available from the corresponding author on reasonable request. Source Data for Figs 2–4 and Extended Data Figs 5 and 6 are available in the online version of the paper.

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