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Significant inequality shown in Chinese provincial export-related fine particle matter pollution and their contributors

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International export is a key driver of fine particulate matter ($PM_{2.5}$) pollution in China, but the specific pollution contribution among foreign consumers to Chinese regions is still unclear. Here, we integrate atmospheric and economic models to explore this contribution. International export accounts for 9.9% of China's ambient $PM_{2.5}$ pollution in 2017, ranging from 7.2% in the Southwest to 13.8% in the East Coast. Material & energy production and transportation are the key producing contributors. The USA and Western Europe are the leading pollution contributors to most provinces. Foreign consumption on construction and manufacturing products contributes most pollution. Over 75.0% of the pollution is embodied in indirect exports and the proportion decreases as the supply chain deepens. Although inland regions only account for 19.8% of China's export volume, their associated pollution contributions reach 65.0%. This study offers a basis for targeted cooperation on pollution mitigation between Chinese provinces and foreign countries.

Past decades have witnessed China's booming economy accompanied by severe fine particulate matter (particles that are 2.5 microns or less in aerodynamic equivalent diameter, $PM_{2.5}$) pollution[1,2]. China's annual average population-weighted $PM_{2.5}$ concentration reached 63 μg/m^3 and the regional hourly concentration could even exceed 1000 μg/m^3 in 2013[3]. With the implementation of the action plan for prevention and control of air pollution[4], China's annual average $PM_{2.5}$ concentration decreased to 43 μg/m^3 in 2017[5] and further to 30 μg/m^3 in 2023[6], but this is still far beyond the World Health Organization (WHO) suggesting air quality guideline (AQG) (WHO AQG) (5 μg/m^3). For further improving national air quality, the Chinese government enacted action plan for continuous improvement of air quality in 2023[7]. This new policy emphasizes targeted emission reductions and the urgent need to identify the driving forces of regional air pollution.

International export has been identified as a key but overlooked driver of Chinese $PM_{2.5}$ pollution[8,9]. Since joining the World Trade Organization (WTO) in 2001, China has become the "Pollution Haven" of developed countries, with their pollution-intensive industries swarming in. Guan et al. [10] have shown that China's exports rank as the second largest contributor among all final demand categories (i.e., exports, capital formation, government consumption and household consumption) to national primary $PM_{2.5}$ emissions. China's exports to different countries exhibit large varieties in trade volume, types of goods, etc. [11], resulting in great heterogeneities in Chinese $PM_{2.5}$ pollution contribution. Lin et al. [12] estimated that the USA alone contributed to ~21% of China's export-related air pollutants in 2006. Li et al. [13] found that the European Union, East Asia and the USA collectively contributed to most (~70%) of China's export-related air pollutant emissions in 2012. Moreover, great disparities exist in the concentration and

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contributors of export-related air pollution over different Chinese provinces, mainly resulting from their differences in export structure and emissions intensity[14]. Wang et al.[8] showed that coastal provinces are responsible for 40% of export values but only 11% of total mortality associated with export-related emissions. Zhang et al.[15] estimated that the emissions suffered by less developed provinces for each yuan of export value is 4–8 times higher than that of developed provinces. However, previous studies mostly treat China[12,13] or the foreign countries[9,15,16] as a whole. To clearly investigate the $PM_{2.5}$ pollution contribution from foreign consumers to China, we need to explore the specific pollution contribution among foreign consumers to detailed regions of China. But this is still unclear mainly due to the lack of dataset for detailed trade flows.

Our study builds the $PM_{2.5}$ pollution contribution-impact relationship among foreign countries and Chinese provinces based on the year 2017, the latest year for which all necessary data are available. We first establish trade flows between foreign countries and Chinese provinces with Chinese provincial customs data and trace provincial emissions triggered by foreign consumption with the multi-regional input-output (MRIO) analysis. Then the atmospheric chemical transport model GEOS-Chem is employed to simulate the distribution of export-related $PM_{2.5}$ concentration in China. Finally, this study conducts structure path analysis (SPA) to investigate air pollution transfer along domestic supply chains triggered by exports. Our research could contribute to understanding the source of provincial $PM_{2.5}$ pollution and its contributors from the aspect of export and support further targeted air pollution mitigation in China.

Results

Export-related provincial $PM_{2.5}$ pollution distribution

Figure 1a shows that Chinese annual average population-weighted $PM_{2.5}$ concentration driven by exports is 5.6 μg/m^3, accounting for 9.9% of the national total $PM_{2.5}$ pollution in 2017. The export-related $PM_{2.5}$ pollution varies greatly across different regions, with 6.4 μg/m^3 in the East Coast and 2.5 μg/m^3 in the Northwest (see Supplementary Fig. 1 for regional classification). Shandong, with large export volume (Supplementary Table 1) and population (Supplementary Fig. 2) in China, suffers most from export-related $PM_{2.5}$ concentration of 9.0 μg/m^3. International export accounts for a larger proportion of $PM_{2.5}$ pollution in Beijing-Tianjin and the East Coast than inland regions (the studied regions except Beijing-Tianjin and the East Coast). For the seven provinces in the East Coast, exports' contribution to total $PM_{2.5}$ pollution all exceeds 10%, even reaching 17.0% in Guangdong. However, for most western provinces, only ~5% of their $PM_{2.5}$ pollution is attributed to exports, even less than 1% in Tibet. Among the analyzed components of export-related $PM_{2.5}$, nitrate is the leading one in most regions (Supplementary Fig. 3), prominent in the province of Shandong, largely related to extensive industrial exports and the accompanying transportation activities[14,16].

Figure 1b depicts that only ~33.8% of Chinese residents live in areas with population-weighted $PM_{2.5}$ concentration lower than 35 μg/m^3 (i.e., Chinese regulated standard) and ~0.4% live in that lower than 5 μg/m^3 (i.e., WHO AQG). As estimated, export-related $PM_{2.5}$ pollution results in ~87.9 million people (~ 6.4% of Chinese population) exposed with population-weighted $PM_{2.5}$ concentration higher than 35 μg/m^3 and ~0.4 million people (~ 0.1% of Chinese population) exposed with that higher than 5 μg/m^3. For 15 provinces, most located in the Central and the East Coast, exports alone contribute over 5 μg/m^3 $PM_{2.5}$, threatening the health of 830 million residents there (Fig. 1a). Notably, the impact of the East Coast export-related $PM_{2.5}$ pollution alone causes the two kinds of the population to reach ~19.3 and ~0.1 million respectively.

Except for the local $PM_{2.5}$ pollution from direct exports, substantial pollution is driven indirectly via domestic trade. A region's indirect export-related $PM_{2.5}$ pollution represents the $PM_{2.5}$ pollution caused by supplying intermediate products for other regions' exports. This contributes to the fact that although the inland regions only account for 19.8% of the national export volume in China (Supplementary Table 1), its contribution to the export-related $PM_{2.5}$ pollution reaches 65.0% (Fig. 1a). Figure 1c shows that 75.4% of Chinese export-related $PM_{2.5}$ pollution is driven by indirect exports. The lowest indirect export-related pollution contribution exists on the East Coast, but still surpasses 70.0%. For some inland provinces, this proportion can reach over 80.0%, with the contribution up to 85.0% in some northern provinces (e.g., 90.1% for Jilin, 90.0% for Qinghai and 85.6% for Inner Mongolia). Exports of the East Coast could account for 27.3% of inland export-related pollution, most dominant in Henan with a pollution contribution of 2.3 μg/m^3, equivalent to 1.4 times of that contributed by local direct exports (Fig. 1d).

Leading contributors of export-related pollution

We further explore the leading contributors to provincial export-related $PM_{2.5}$ pollution in China. Figure 2 shows the leading foreign consumers contributing to China's export-related $PM_{2.5}$ pollution. In most provinces, the USA is the top driver and Western Europe comes second, collectively contributing to 37.9% of national export-related $PM_{2.5}$ pollution in 2017 (Fig. 2a, b). The USA contributes most to Fujian (22.9% of its total export-related pollution and only the ratio is shown in the following) and Guangdong (22.8%), while Western Europe contributes most to Shanghai (18.8%) and Shanxi (18.6%). In Tibet, Xinjiang and Yunnan, their border region Rest of Asia surpasses the USA as the largest contributor, driving 35.7, 32.6, and 23.6% of their export-related $PM_{2.5}$ pollution, respectively. For Liaoning, the Rest of East Asia is the second top driver, driving 16.2% of its total export-related pollution. Details for the major foreign contributors to provincial export-related $PM_{2.5}$ pollution are listed in Supplementary Table 2.

However, by contrasting Fig. 2b, c, we find distinct differences between the foreign consumers' contribution to pollution and export volume. For example, although the Rest of East Asia contributes most to Shandong's export volume, it only ranks fourth among the export-related pollution contributors. This is because industrial products with high emission intensity dominate Shandong's exports to the USA. For example, the sectors "Machinery and equipment" and "Motor vehicles and parts" collectively contribute 25.4% of exports to the USA while the contribution accounts for only 9.1% of the exports to Rest of East Asia. The sector "Wearing apparel" dominates Shandong's exports to Rest of East Asia (accounting for 23.5%), with an export-related emission intensity of 0.04 g/US$, while the export-related emission intensity of the sector "Motor vehicles and parts" to the USA is about twice that amount. Similarly, although Rest of Asia contributes only 10.4% of the export volume of Liaoning, it is the third largest contributor, accounting for 15.2% of the export-related pollution. This is largely due to the high emission intensity of the sector 'Machinery and equipment' in Liaoning (0.12 g/US$), accounting for 37.9% of its exports to Rest of Asia.

Given the expensive computational costs, we use atmospheric pollutant equivalents (APE)-converted emissions instead of $PM_{2.5}$ concentration to facilitate the analysis of the sectoral contributors. Figure 3a unveils the leading sectors contributing to China's export-related emissions from both consumption- and production-based perspectives. Overall, China's export-related emissions for species except NH_3 are mainly resulted from material production (mainly from the sectors "Ferrous metals", "Mineral products nec", "Metals nec", "Chemical products" and "Petroleum, Coal products"), energy production (mainly from the sector "Electricity") and transportation (mainly from the sectors "Transport nec" and "Water transport"), and the top five sectors of each species collectively contributes to nearly or over half of the total emissions. Foreign consumption on construction (mainly from the sector 'Construction') and manufacturing products ("Machinery and equipment nec", "Computer, electronic and optical products", "Motor vehicles and parts" and "Electrical equipment") contributes most, together accounting for over 80% of the export-related emissions. Especially, the production sector 'Ferrous metals' is responsible for 65.6% of China's export-related other primary $PM_{2.5}$ emissions, 54.9% of CO emissions and 28.8% of SO_2 emissions, with over 30% of these emissions driven by foreign consumption in the sectors "Construction' and "Machinery and equipment nec'. The export-related emissions of NH_3 are mainly driven by foreign consumption on the sectors "Wearing apparel" and "Food products nec",

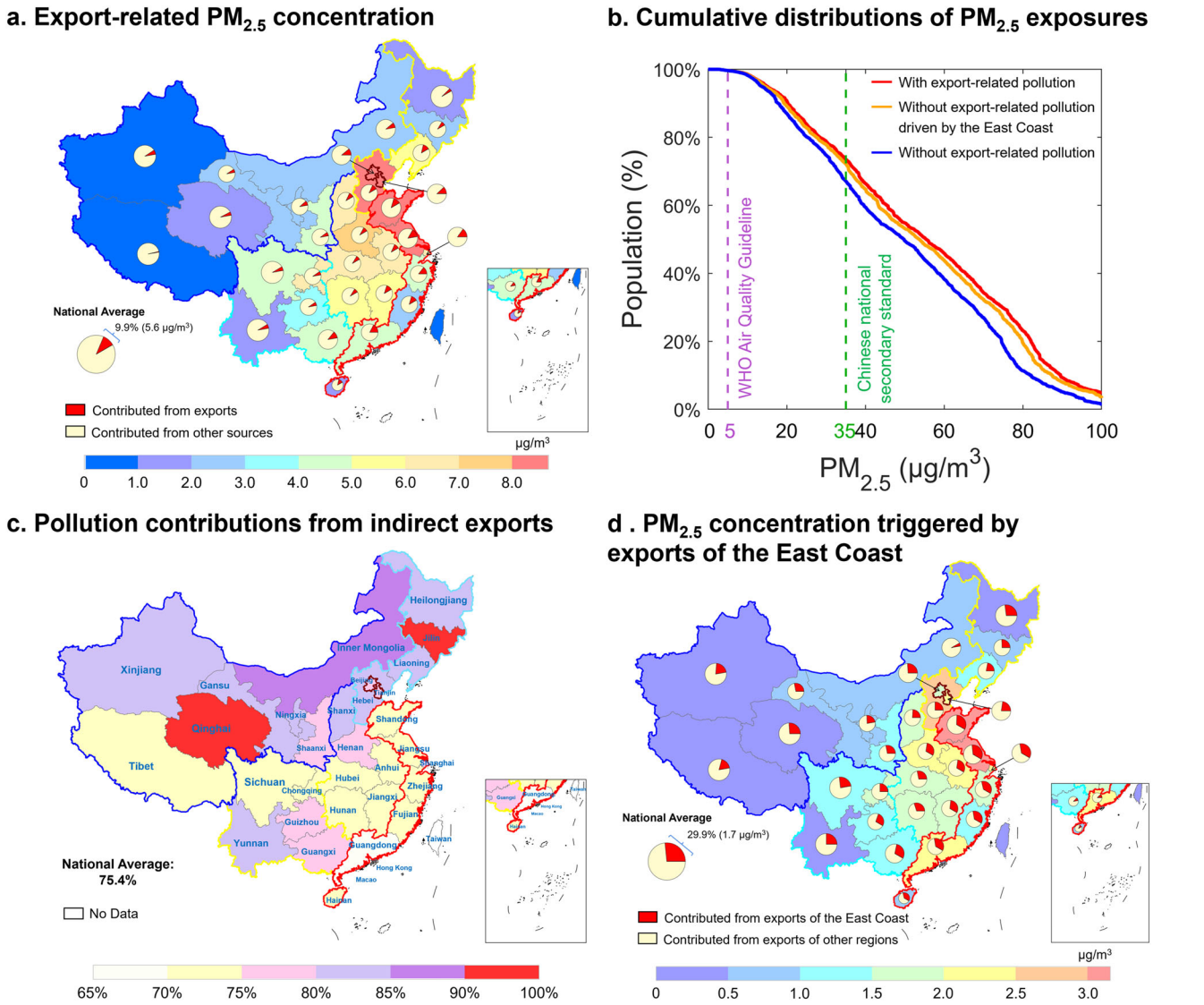

Fig. 1 | China's export-related $PM_{2.5}$ pollution in 2017. a Population-weighted annual average $PM_{2.5}$ pollution driven by exports and its share in total $PM_{2.5}$ pollution in each province in 2017. (detailed gridded concentration for $PM_{2.5}$ components could be found in Supplementary Fig. 3) **b** National cumulative distributions of $PM_{2.5}$ exposures. **c** The contribution from provincial indirect exports in total export-related $PM_{2.5}$ pollution. **d** Population-weighted annual average $PM_{2.5}$ pollution driven by exports of the East Coast and its share in total export-related $PM_{2.5}$ pollution. (detailed gridded concentration for $PM_{2.5}$ components could be found in Supplementary Fig. 4).

stimulating Chinese exports of agricultural products (mainly from sector "Bovine cattle, sheep and goats, horses") and raw materials (mainly from sectors "Vegetables, fruit, nuts" and "Crops nec") for further processing. As the primary sources of NH_3 are nitrogen fertilizer application and livestock manure[17], "Bovine cattle, sheep and goats, horses" and "Vegetables, fruit, nuts" are the largest emitters, collectively contributing to 60.9% of China's export-related NH_3 emissions.

Figure 3b exhibits the major foreign contributors to the top two consuming sectors. For export-related emissions of all analyzed species, the USA, Western Europe, Rest of Asia and Rest of East Asia are usually the major consumers of the top two consuming sectors "Construction" and "Machinery and equipment nec". As the top two contributors to China's export-related $PM_{2.5}$ pollution, consumption of the USA and Western Europe accounted for nearly 40% of various export-related emissions. Contribution from the USA is predominantly driven by the consumption of sectors "Machinery and equipment nec" and "Motor vehicles and parts", while contribution of Western Europe is largely linked to the demand from the sector "Construction". For the emissions of NH_3, contributions from the USA and Western Europe are primarily related with their consumption on the sectors "Wearing apparel" and "Food products nec". Notably, the consumption of Rest of East Asia exhibits a relatively high contribution to the sector "Food products nec", accounting for 26.7% of the total.

Figure 3c shows the major provincial contributors to the top two producing sectors. The export-related emissions are mainly emitted from the provinces Shandong, Guangdong, Jiangsu and Hebei, partly due to their large export volume of industrial products. Inner Mongolia's contribution to the export-related emissions of SO_2 and NO_x is also prominent due to its large production in the sector "Electricity". Shanxi's large contribution to the export-related emission of BC is mainly linked to its production in the sector "Petroleum, coal products". Hebei, leveraging its abundant iron and steel resources, exhibits a predominantly high contribution (over 15%) to export-related emissions of multi-species from the sector "Ferrous metals". Shandong, as the largest agriculture exporter in China[18], is the leading emitter of NH_3, with contribution of 20.2% and 19.0% to the emissions of the top two sectors "Bovine cattle, sheep and goats, horses" and "Vegetables, fruit, nuts", respectively.

To help identify whether China's exports are for short-lived consuming goods or long-lived capital assets, we further separate the export-related

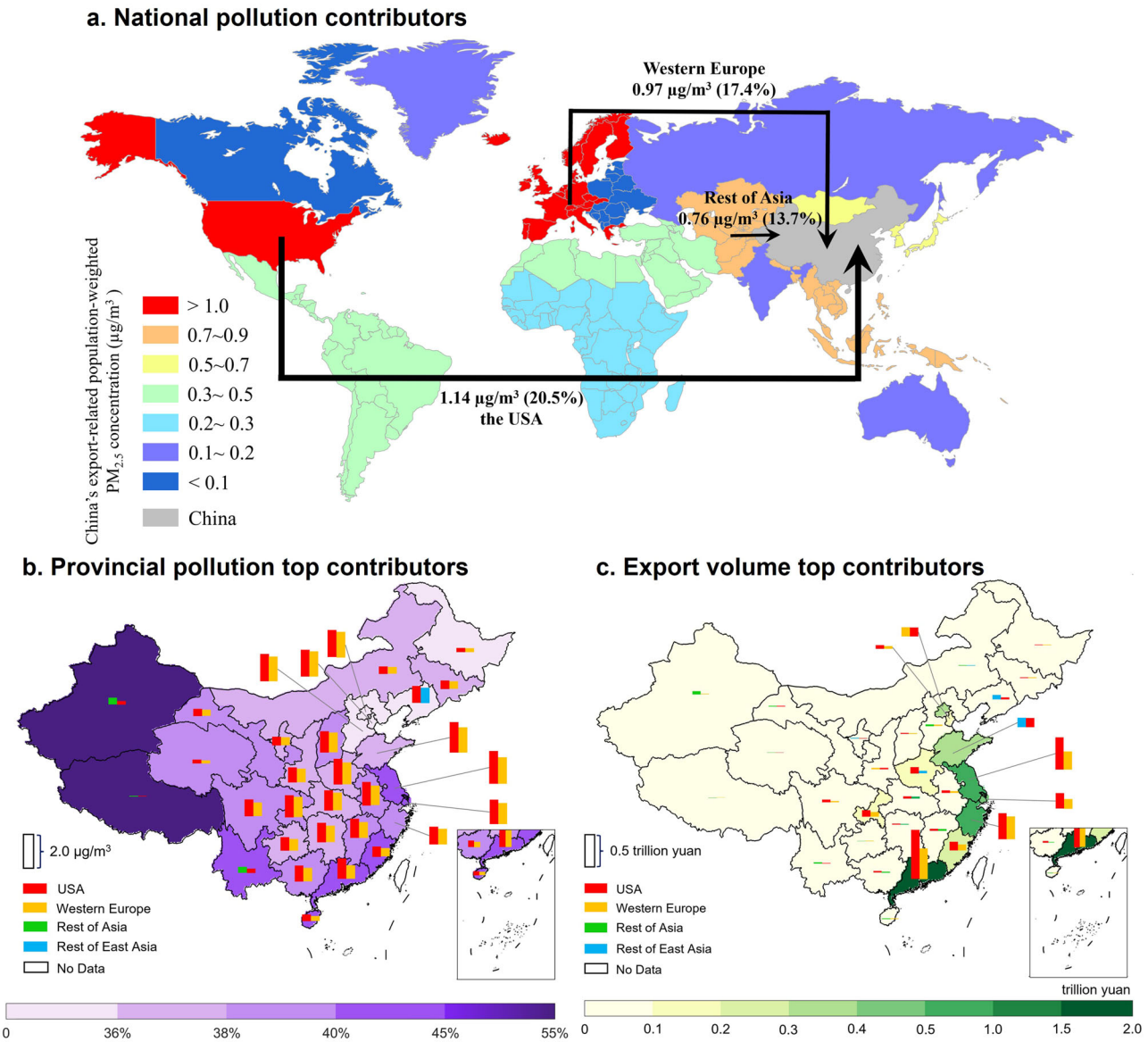

Fig. 2 | Leading contributors to China's export-related $PM_{2.5}$ pollution. a Top foreign contributors to China's export-related $PM_{2.5}$ pollution. **b** Top two foreign contributors to provincial export-related pollution (the bars) and their contribution proportion in total export-related pollution (the shadings). **c** Top two foreign contributors to provincial export volume (the bars) and the provincial export volume (the shadings). Here, the 160 regions around the world are classified into 13 regions according to their geographical locations, which can be found in Supplementary Fig. 11.

emissions into capital- (gross fixed capital formation) and consumption-driven (household and government consumption) categories[19] in Supplementary Fig. 5. For NO_x, NH_3, BC and OC, over 50% of China's export-related emissions are consumption-driven, due to their close connection with daily consuming goods such as food products (relying on agricultural production) and household manufacturing products (relying on energy and industrial production). In contrast, export-related emissions of CO, SO_2 and other primary $PM_{2.5}$ are predominantly capital-driven. This pattern is dominated by production of the sector 'Ferrous metals', which accounts for 54.9, 28.8, and 65.6% of CO, SO_2 and other primary $PM_{2.5}$ export-related emissions, respectively, with the majority (57.3, 56.8, and 55.7%) attributed to capital-driven demand, mainly on infrastructure, machinery and industrial equipment.

Pollution flow along the interprovincial supply chains

In order to clarify the drivers of indirect exports-driven pollution shown in Fig. 1c, we further explore the emission flows along the domestic supply chains driven by international export with Fig. 4. In the export-related emissions of each PL (i.e., Production Layer), the proportion of emissions driven by other regions' exports is 62.5% at PL^1, which decreases to 46.8% at PL^2 and 39.2% at PL^3. This decreasing trend is related to the relatively strong dependence on local supplies of raw materials at deep stages of supply chains in each province[20]. For example, the sector "Ferrous metals" accounts for only 0.1% of China's provincial local direct export-related emissions at PL^1, with their contribution escalating to 13.9% at PL^3.

Besides, Supplementary Fig. 6 shows that the export-related emissions mainly occur at upstream of supply chains. We find that only 0.8% (in Jilin) ~ 11.0% (in Beijing) of the export-related emissions in each province occur at PL^0. National export-related emissions discharged at PL^4 and all deeper layers could even reach 41.7%, especially for inland regions, with 59.0% in Qinghai, 54.7% in Inner Mongolia and 53.7% in Shanxi. Supplementary Table 3 further shows that the provincial export-related emissions at different PLs are mainly discharged from pollution-intensive sectors like "Ferrous metals" and "Mineral products nec". Besides, the emissions of sectors producing raw materials increase as the supply chain deepens, as these sectors play a pivotal role in supplying raw

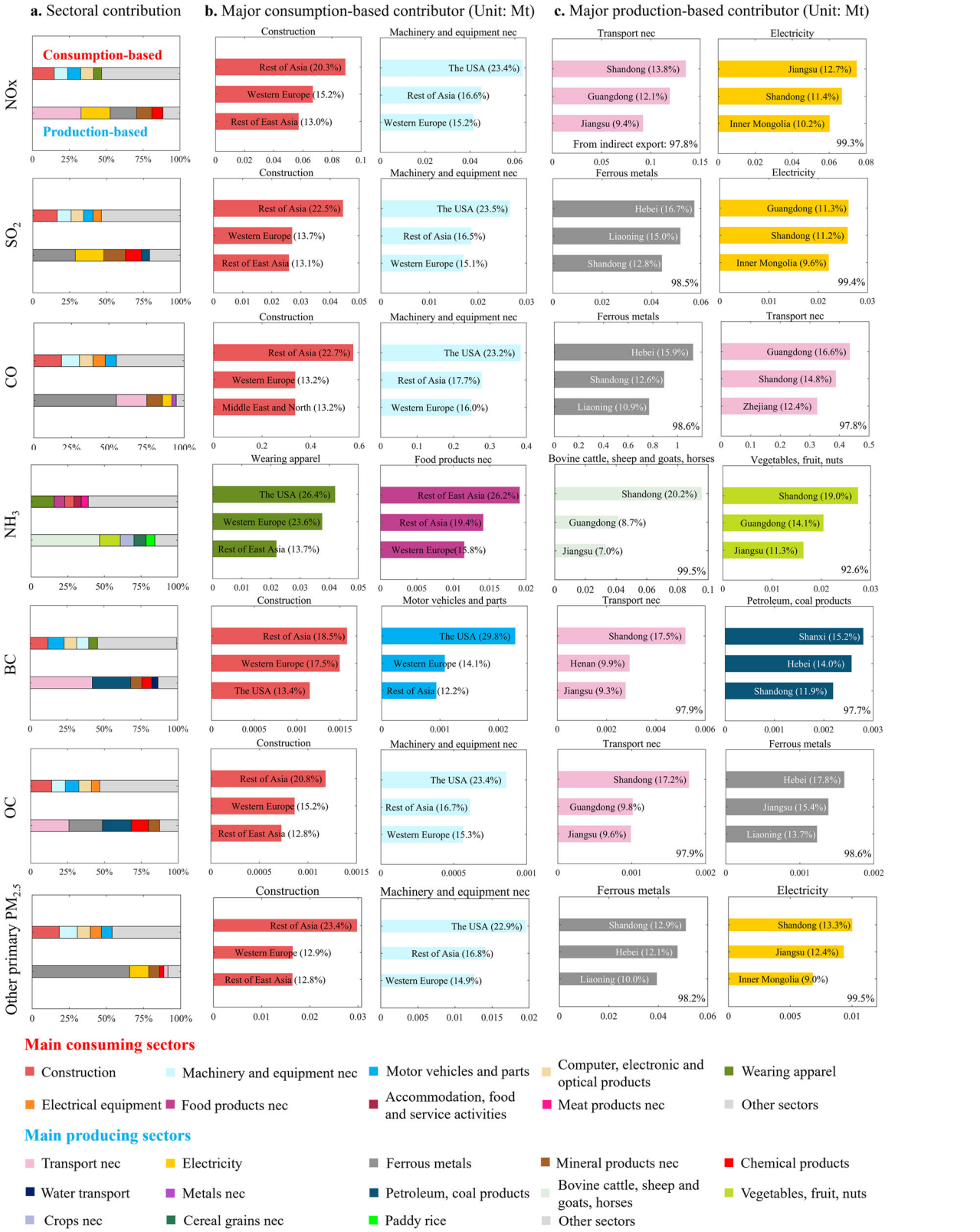

Fig. 3 | Sectoral contributions to export-related air pollutant emissions in China. **a** Consumption-based (foreign countries as consumers) and production-based (Chinese provinces as producers) sectoral contribution. **b** Major foreign contributors to the top two consuming sectors. **c** Major provincial contributors to the top two producing sectors and the bottom right percentage shows the contributions from indirect exports. The percentage on each bar of panels **b** & **c** illustrates the contribution proportion of each region to the total export-related emissions of this sector. The "nec" in the sector name means "not elsewhere classified", referring to economic activities or industries that cannot be clearly classified into other specific sectors.

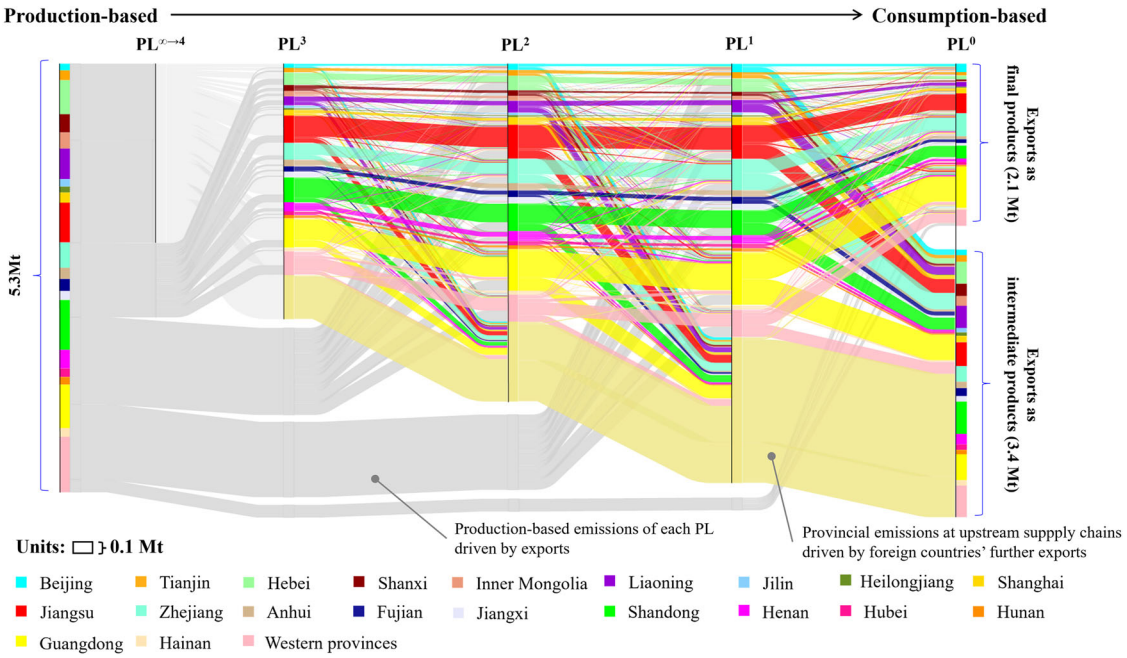

Fig. 4 | Export-related emission flows along the interregional supply chains in 2017. Here, all emissions are converted by APE. The leftmost bar shows the provincial production-based emissions driven by national exports. The rightmost bar denotes the provincial consumption-based export-related emissions, including emissions driven by international exports as final consumed products (i.e., the upper bar) and as intermediate products for foreign countries' further exports (i.e., the lower bar). The gray flow represents the production-based emissions of each production layer (i.e., PL) driven by national exports. The pale yellow flows represent provincial emissions at upstream supply chains driven by foreign countries' further exports. For example, the flows between PL^0 and PL^1 represent emissions from all provinces embodied in the output of foreign countries at PL^1 purchased by foreign countries at PL^0. The detailed explanation for other flows between PLs could be found in Methods. The emissions of foreign countries driven by Chinese exports are not included here. Given the small quantity of emission flows in Western provinces, we integrate them together into one single entity according to the regional classification in Supplementary Fig. 1.

materials for subsequent PLs. For example, the contribution from the sector "Electricity" to national export-related emissions rises from 7.4% at PL^1 to 18.2% at PL^3.

The rightmost bar in Fig. 4 illustrates China's provincial consumption-based export-related emissions, including 2.1 Mt APE-converted emissions driven by exports as final consumed products and 3.4 Mt from exports as intermediate products for foreign countries' further exports. For the inland exporters, the emission contributed from intermediate products for foreign countries' further exports surpasses that from final consumed products. For example, in Jilin and Inner Mongolia, the consumption-based export-related emissions driven by exports as intermediate products are 14.8 (~ 0.1 Mt) and 12.2 (~ 0.1 Mt) times as much as those driven by exports as final products, respectively. However, the opposite is true for the East Coast. For instance, the consumption-based export-related emissions of Beijing and Guangdong driven by exports as intermediate products are only 0.5 (~ 0.1 Mt) and 0.6 (~ 0.3 Mt) times that driven by exports as final products.

Supplementary Fig. 7 illustrates the interprovincial emission transfer disparity (i.e., the difference between other provinces' emissions driven by this province's exports and emissions in this province driven by other provinces' exports) and the major interprovincial emission transfer disparity flows (i.e., the difference between the two provinces' emissions driven by the exports of each other). Provinces with positive interprovincial emission transfer disparity, which are concentrated in the eastern coastal regions, indicate that these provinces tend to have emission outflow, and the opposite is true for inland regions. The top ten interprovincial emission transfer disparity flows are predominantly driven by exports in the East Coast, especially in Guangdong, Zhejiang and Jiangsu. As estimated, the inland interprovincial emission flows driven by the demand of the East Coast are 81.8, 78.2, and 73.7% at PL^1, PL^2, and PL^3, respectively, while the contribution proportion of the opposite direction is only 23.4%, 22.7% and 20.1%. Notably, 73.6% of Hunan's interprovincial flows at PL^1 are triggered by the East Coast, with Guangdong responsible for 40.1% of this contribution. Supplementary Table 4 lists the top 20 interprovincial supply-chain paths inducing export-related emissions. These paths are mainly driven by the demand of provinces in the East Coast, especially Guangdong and Zhejiang. For example, 14 out of the top 20 paths start from Guangdong and totally result in 0.14 Mt APE-converted emissions. From the supply viewpoint, inputs of sectors "Ferrous metals", "Mineral products nec" and "Metals nec" are major contributors among these top paths. "Ferrous metals" plays an important role in paths related to Hebei. For example, 'Ferrous metals" contributes 49.1 and 46.6% in the paths Guangdong-to-Hebei and Zhejiang-to-Hebei, respectively. From the demand viewpoint, sectors "Computer, electronic and optical products" and "Electrical equipment" take the lead (Supplementary Table 5). The manufacturing sectors in the East Coast import large quantities of raw materials from inland regions, thus outsourcing massive air pollution.

Discussion

Despite the remarkable achievements in alleviating air pollution, China's $PM_{2.5}$ concentration is still far from reaching the WHO AQG. International exports have been identified as a key driver of Chinese air pollution. Based on our results, international export is accountable for 9.9% of Chinese $PM_{2.5}$ pollution in 2017, resulting in 87.9 and 0.4 million more people being exposed to $PM_{2.5}$ concentration surpassing Chinese regulated standard (35 μg/m^3) and WHO AQG (5 μg/m^3), respectively. A group of developed countries (i.e., the USA, Western Europe and several Asian countries) accounts for the largest share of China's export-related $PM_{2.5}$ pollution, which aligns with the implications in previous studies based on carbon footprint[21,22]. However, due to the lack of dataset for detailed trade flows, existing studies mostly treat China or the foreign countries as a whole, ignoring the heterogeneities of pollution suffering in different Chinese regions and their drivers. By establishing the detailed trade flow network among Chinese provinces and foreign countries, our study shows that $PM_{2.5}$

pollution contribution from exports could range from 13.8% in the East Coast to 7.2% in the Southwest. The USA and Western Europe take the lead in driving most provinces' export-related pollution except for some inland provinces (e.g., Xinjiang, Yunnan), where their neighboring Asian countries contribute the most. Severe regional inequalities also exist in the consumption- and production-based sectoral contributors. Our study emphasizes the pollution-driving effect of the East Coast's exports on the inland regions in China. As estimated, the inland contribution proportion to national export volume is only third of that to national export-related $PM_{2.5}$ pollution, for 77.4% of inland export-related $PM_{2.5}$ pollution is indirectly driven by exports of other regions, in which the East Coast plays an important role. The supply chain analysis further reveals that the proportion of the indirect export-related emissions decreases as the supply chain deepens.

The establishment of foreign countries-Chinese provinces trade flow and pollution contribution relationship offers a basis for international cooperation on air pollution mitigation. As the "World's Largest Factory," China has suffered a lot from the air pollution triggered by international export since joining the WTO[23,24]. The related developed countries are supposed to help with improving China's air quality through international cooperation[25,26]. However, cooperation strategies based on large scales, such as country-to-country usually fail to play an effective role in pollution mitigation. Our study identifies the key drivers of each province, facilitating the effectiveness of international cooperation on pollution mitigation by promoting targeted international cooperation.

Based on our results, the provincial air pollution mitigation may be inefficient by simply restricting exports to countries with high export volume contributions. For example, although the Rest of East Asia dominates Shandong's export volume, the USA contributes most to its export-related $PM_{2.5}$ pollution, partly because of the substantial export of industrial products with high emission intensity to the USA. On the one hand, the government should strengthen interventions on provincial exports, such as imposing restrictions or prohibitions on pollution-intensive commodities from processing exports. Particular attention should be given to products involved in indirect exports[27], which account for the majority of China's export-related pollution. On the other hand, developed foreign countries are supposed to export advanced green production technologies to the provinces from which they export, such as the transition to renewable energy. Thus, provinces can effectively address green trade barriers established by developed countries and mitigate export-related pollution. Under Chinese government's strong propulsion of the integration of domestic and foreign trade[28], the industries and enterprises are encouraged to be with clean and sustainable production in line with international environmental standards. Targeted international cooperation on green production could also help with achieving this goal.

The clarification of China's domestic pollution flows driven by international export highlights the importance of domestic interregional joint pollution control. According to the hypothesis of pollution haven, developed regions' emission reduction is largely promoted by outsourcing emissions to less developed regions[29,30]. However, implementing policies targeting emission reduction is more challenging for less developed regions as limited funds are provided for updating their technologies and infrastructure[31]. Thus, inland net exporters of export-related emissions should struggle to transform pollution-intensive industries and enhance cooperation with domestic trade partners, while coastal net importers should provide financial or technical support to achieve joint pollution control. To achieve this, a clarification of the domestic transboundary pollution transfer is the basis. Therefore, we further explore the detailed emission flows along the supply chains and find that inland heavy industries contribute the most emissions to meet national exports. To reduce export-related $PM_{2.5}$ pollution in China, it is urgent for these industries to raise their pollution control criteria and accelerate energy transformation from fossil fuels to renewable energy. In addition, the tendency of exporters to choose trade partners with a green production process could push emission reduction in heavy industries. We suggest policymakers trigger interventions not only on the production behaviors of producers, but also on their trade partners[15,22], e.g., adding incentive mechanisms for the green industrial chain.

Although our study is based on the year 2017 due to the data limitation, our analyzes can also well support China's related policy regulation in the present situation. Changes in China's emission patterns, export volume and trade structure would inevitably lead to disparities in the China's export-related $PM_{2.5}$ pollution between the present situation and that in 2017. In addition, some international political events would also have an impact, e.g., the Sino-US trade war may weaken the leading role of the USA in driving China's export-related pollution. With emission and export data in 2020, we test the potential impact and find that although the provincial export-related emissions in 2017 would be remarkably different from the present situation in volume, the changes in the proportion distribution of emission contribution would be relatively small (Supplementary Fig. 8). We suggest more attention on the pollution responsibility reallocation based on consumption and encourages both international and domestic interregional cooperation on emission reduction technologies, environmental policy regulation, etc. Our study not only contributes to the export-related pollution mitigation in China, but also acts as a reference for pollution control in other countries as "Pollution Haven".

Methods

Analytical framework

To explore the provincial export-related $PM_{2.5}$ pollution triggered by foreign countries' consumption, our approach includes three major components. First, we trace provincial export-related air pollutant emissions by establishing a Foreign countries-Chinese provinces linked MRIO model. Second, we apply the chemical transport model GEOS-Chem to simulate ambient $PM_{2.5}$ concentrations in China induced by exports. Third, the SPA is applied to investigate emission transfer along each tier of the domestic supply chains. The analytical framework of our study is summarized in Supplementary Fig. 9.

Foreign countries- Chinese provinces linked MRIO table

A powerful tool to trace $PM_{2.5}$ pollution flows among different regions is the MRIO analysis and the basic data is the MRIO table. Thus, we first establish trade flows between foreign countries and Chinese provinces by linking global and Chinese provincial MRIO tables based on the year 2017, the latest year available for both tables.

A number of studies have employed multi-regional linked MRIO model to investigate environmental footprint between a specific country and other countries[8,32–39]. However, many existing analyzes focusing on China's environmental challenges through this approach exhibit certain limitations. For example, the results in some studies are too outdated to be used in contemporary environmental studies in China[8]. Some studies apply the national average economic structure to each province when linking the two MRIO tables, leading to great uncertainties in estimating the economic flows between each province and foreign countries[32,34,37,39]. Moreover, there exist mismatches between sectors in the Chinese provincial MRIO table and the ones in the global MRIO table, but most studies use relatively rough methods in sector matching due to the lack of detailed sectoral economic data[32,37]. Besides, almost none of the previous studies expand the agricultural sector from one aggregated sector into several detailed subsectors with sectoral detailed statistical data.

Our study refined existing methodologies of building the Foreign countries-Chinese provinces linked MRIO table by solving the above problems. The global MRIO table is obtained from the Global Trade Analysis Project (GTAP, https://www.gtap.agecon.purdue.edu/databases/v11/) version 11[40], covering trade flows between 65 economic sectors (Supplementary Table 6) of 160 regions (Supplementary Table 7). China's provincial MRIO table used in our study is obtained from Zheng et al. [41], covering trade flows among 42 economic sectors (Supplementary Table 8) of 31 mainland provinces (data for Hong Kong, Macao and Taiwan are not available).

The framework of the FC-CP linked MRIO table is shown in Supplementary Fig. 10. The FC-CP linked MRIO table can be divided into four matrices and the methods to compile each matrix are shown as follows:

1). The matrix of foreign countries' trade flows ($Z^{F\text{-}F}$ and $D^{F\text{-}F}$). $Z^{F\text{-}F}$ and $D^{F\text{-}F}$ are directly derived from the global MRIO table and the data of Chinese mainland are removed.

2). The matrix of interprovincial trade flows ($Z^{P\text{-}P}$ and $D^{P\text{-}P}$). The compilation of these two matrices is mainly based on the Chinese provincial MRIO table. Here we match its sectors with those of the global MRIO table. The mapping between 42 sectors of Chinese provincial MRIO table and the 65 sectors of the global MRIO table is according to Supplementary Table 8. The main difference between the two tables lies in the agricultural sectors. There's only one aggregated agricultural sector in China's provincial MRIO table, while there are 14 specific agricultural sectors in the global MRIO table. We collect detailed agricultural output value data from provincial yearbook[42] and allocate them into 14 sectors, thereby obtaining the proportions of output for 14 agricultural sectors in each province. Subsequently, we expand the agricultural sector in China's MRIO table based on these proportions. The output value of detailed agricultural sector s of province r can be calculated as:

$$V_s^r = V_g^r \times \frac{O_s^r}{O_g^r} \tag{1}$$

where V_g^r refers to the province r's total output value of the aggregated agricultural sector in provincial MRIO table; O_g^r refers to the total agricultural output value from the yearbook of province r; O_s^r refers to the output value of sector s from the yearbook data.

For other aggregated sectors, we apply a similar approach. However, available product output values cannot always meet the needs of the allocation of sectors and these situations are shown as follows with their corresponding treatments: (1) Provincial output value of grains are obtained from the yearbook and we use them to subtract the value of rice and wheat as the output value of the sector 'Cereal grains nec'; (2) We multiply the provincial price of cattle meat by corresponding provincial production to get the output value of the sector 'Bovine meat products' and the missing provincial price is replaced by the national average; (3) Furniture is excluded from the wood products sector in the global MRIO table but included in the provincial MRIO table. We calculate the proportion of furniture in wood products of each province with data from the yearbook and move the output value of this part to the sector 'Manufactures nec'.

3). The matrix of China's exports ($Z^{P\text{-}F}$ and $D^{P\text{-}F}$). These two matrices and China's import matrices, as mentioned below, are key components in connecting the global and China's MRIO tables. The customs export and import data are essential for building these matrices. The utilization of customs data can effectively reflect differences of international trade structures across provinces[33] and we obtain the data from the Chinese customs yearbook[43]. The matching tables of regions and sectors-HS code (Harmonization Code System) are built for matching customs export data with corresponding regions and sectors in the global MRIO table.

Based on the export data, we can only find out the regional importers of each provincial sector, but the exact sector in a foreign country the products head to is still unclear[35]. To solve this problem, the input ratio of a provincial sector to the sectors of a foreign country is based on the national input ratio and calculated based on the global MRIO table. Subsequently, we divide the export matrix into $Z^{P\text{-}F}$ and $D^{P\text{-}F}$ based on the ratios of economic flows obtained from the global MRIO table. The input value of sector s in province r to sector e in the foreign country f in the $Z^{P\text{-}F}$ can be expressed as:

$$P_{rs}^{fe} = E_{rs}^{f} \times \frac{Pm_{cs}^{fe}}{Pm_{cs}^{f}} \times \frac{Zm_{cs}^{f}}{Zm_{cs}^{f} + Dm_{cs}^{f}} \tag{2}$$

where E_{rs}^f refers to the export value of sector s in province r to the foreign country f from the customs export data; Pm_{cs}^{fe} and Pm_{cs}^{f} refer to the input value of sector s in China to the sector e the foreign country f and to all sectors in the foreign country f, respectively; Zm_{cs}^{f} and Dm_{cs}^{f} refer to the input value of sector s in China to intermediate demand and final demand of region f, respectively. The input values are obtained from the global MRIO table.

The customs data includes various types of trade, among which we did not consider the items "processing trade with imported materials", "equipment imported for processing trade" and "bonded zone warehousing and re-exported goods", as they do not contribute to China's export-related emissions. The export values of provincial sectors in China's provincial MRIO table are then used to adjust the sectoral total export matrix in the linked MRIO table.

4). The matrix of China's imports ($Z^{F\text{-}P}$ and $D^{F\text{-}P}$). The establishment of $Z^{F\text{-}P}$ and $D^{F\text{-}P}$ is similar to that of the export matrix. Differently, through the import customs data we can find out the exact foreign sector the import products come from, but the problem is finding out the provincial sector these products are consumed. Thus, the regional sector's input ratio to a provincial sector is calculated based on the global MRIO table. The import values of provincial sectors in China's provincial MRIO table are then used to adjust the sectoral total import matrix in the linked MRIO table.

So far, we have an original linked MRIO table which is unbalanced between input and output. Therefore, we employed the RAS balancing technique—a widely recognized method for input-output table optimization[32,34,38,44]—which minimizes structural deviations from the original matrix while ensuring adherence to predefined row and column constraints. Specifically, we integrated foreign trade and economic data from the GTAP to adapt China's provincial MRIO framework, thereby maintaining consistency with global trade patterns and enhancing the reliability of the adjusted table.

Chinese provincial customized emission inventory

For calculating air pollutant emissions embodied in exports of Chinese provinces, a set of Chinese provincial emission inventory matching with the Foreign countries-Chinese provinces linked MRIO table is needed. The pollutants analyzed in our study include NO_X, SO_2, CO, NH_3, BC, OC and other primary $PM_{2.5}$, which are the important precursors or primary particles of $PM_{2.5}$.

In this study, we establish a set of customized Chinese provincial emission inventory based on two sets of public emission inventories, i.e., Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) (GAINS, http://www.iiasa.ac.at/web/home/research/researchPrograms/air/Asia.html)[45] and Multi-resolution Emission Inventory for Climate and air pollution research (MEIC, http://www.meicmodel.org/)[46,47]. MEIC contains only five integrated sectors (i.e., Power, Industry, Residential, Transportation, and Agriculture), which is far from matching the 65 sectors in MRIO table. To expand the number of sectors, we further combine MEIC with GAINS, which includes 56 detailed emission sectors. GAINS updates its emission inventory every five years and lacks emission data for our study year 2017. Based on the emissions of 2015 and 2020, we apply linear interpolation to estimate emissions in 2017. We first use the emission proportion of 56 sectors obtained from GAINS to expand the number of sectors in MEIC:

$$E_i^n = f_{ij}^n \times E_j^n \tag{3}$$

where E_i^n is the emission of sector i ($i = 1, 2, \ldots, 56$) in province n ($n = 1, 2, \ldots, 31$). E_j^n represents the emission of the corresponding aggregated sector j ($j = 1, 2, \ldots, 5$) of MEIC. f_{ij}^n represents the ratio of subsector i's emission in GAINS to the total amount of all subsectors corresponding to the aggregated sector j in MEIC in province n. The sector mapping between GAINS and MEIC can be found in Supplementary Table 9.

We then match the sectors between GAINS and GTAP (see Supplementary Table 9) and extend the emission data to 65 sectors with the sectoral output ratio of the global MRIO table. The emissions associated with private vehicles driving (e.g. private cars, mopeds and motorcycles) and residential

activities (e.g., daily cooking and heating) are excluded from our inventory following our previous work[48], as these activities do not participate in economic activities. Finally, we develop a hybrid customized emission inventory for 2017, including 31 provinces, 65 sectors and seven air pollutants (i.e., NO_X, SO_2, CO, NH_3, BC, OC, and other primary $PM_{2.5}$). In addition, this study divides the agricultural sector into 15 detailed subsectors to match with those in global MRIO table and we used the detailed emission inventory of NH_3 developed by Chen et al. [49], including provincial NH_3 emissions from 14 categories of agricultural products and see Supplementary Table 10 for details, to improve the emissions of these subsectors.

Calculation of export-related emissions

MRIO analysis has been widely used in environmental studies[22,50,51]. In this study, we use MRIO analysis to trace Chinese provincial export-related emissions. The basic MRIO model could be described as:

$$\boldsymbol{X} = \boldsymbol{AX} + \boldsymbol{Y} \tag{4}$$

where $\boldsymbol{X}$ refers to the total output vector; $\boldsymbol{A}$ is the matrix of technical coefficients that shows the direct inputs required to produce one unit of output; $\boldsymbol{Y}$ is the final demand vector.

In matrix form, Eq. (4) could be written as:

$$\begin{pmatrix} x_1 \\ x_2 \\ \cdots \\ x_n \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ \cdots \\ x_n \end{pmatrix} + \begin{pmatrix} y_1 \\ y_2 \\ \cdots \\ y_n \end{pmatrix} \tag{5}$$

where n ($n = 1, 2, \ldots, 65$) represents the economic sectors involved in our research; $a_{i,j}$ denotes the direct input of sector i required to produce one unit of output of sector j, which could be expressed as:

$$a_{ij} = z_{ij}/x_j \tag{6}$$

where z_{ij} refers to the intermediate products produced by sector i and consumed by sector j; x_j refers to the total output of sector j.

Equation (4) could be transformed as:

$$\boldsymbol{X} = (\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{Y} \tag{7}$$

Here, $\boldsymbol{I}$ is the identity matrix; $(\boldsymbol{I} - \boldsymbol{A})^{-1}$ is the Leontief matrix (or written as $\boldsymbol{L}$) representing the direct and indirect requirements of each sector to satisfy the final demand $\boldsymbol{Y}$.

Thus, the emissions driven by final demand $\boldsymbol{Y}$ could be calculated as:

$$\boldsymbol{E} = \boldsymbol{F}(\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{Y} \tag{8}$$

Here, $\boldsymbol{F}$ is the emission intensity (i.e., emissions per unit of output) and the emission intensity of sector i could be calculated as:

$$f_i = e_i/y_i \tag{9}$$

in which e_i and y_i refers to the total emissions and the total output of sector i, respectively.

Based on Eq. (8), the export-related emissions of province r could be calculated as:

$$\boldsymbol{EEE_{re}} = \boldsymbol{F}_r(\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{Y}_d^e \tag{10}$$

Here, $\boldsymbol{EEE}_{re}$ is the emissions occur at province r driven by international exports to the foreign country e; $\boldsymbol{F}_r$ is a $1 \times N$ vector of the sectoral emission intensities for province r, where N shows the number of sectors; $\boldsymbol{Y}_d^e$ is a $N \times 1$ vector shows the products from each province consumed by final demand d (i.e., gross fixed capital formation, household consumption and government consumption) in foreign country e. Here, $\boldsymbol{Y}_d^e$ includes two parts, i.e., $\boldsymbol{Y}_d^{re} = (00 \cdots y^{re} \cdots 00)'$ (the products from province r that are consumed by country e as final demand) and $\boldsymbol{Y}_d^{se} = (y^{1e}\, y^{2e} \cdots y^{(s-1)e}\, 0\, y^{(s+1)e} \cdots y^{(N-1)e}\, y^{Ne})'$ (the products from other provinces that are consumed by country e as final demand).

Thus, Eq. (10) can be separated into two parts:

$$\boldsymbol{EEE}_{dre} = \boldsymbol{F}_r(\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{Y}_d^{re} \tag{11}$$

$$\boldsymbol{EEE}_{ire} = \boldsymbol{F}_r(\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{Y}_d^{se} \tag{12}$$

Here, $\boldsymbol{EEE}_{dre}$ is the direct export-related emissions of province r, i.e., emissions from production of goods in province r directly used for exports of province r; $\boldsymbol{EEE}_{ire}$ is the indirect export-related emissions of province r, i.e., emissions from production of goods in province r used for other regions' further exports. For example, Shandong produces ferrous metals for the vehicle export in Jiangsu, thus Shandong will suffer from the indirect export-related emissions due to the export in Jiangsu.

Due to the expensive computational costs, we use air pollutant emissions instead of $PM_{2.5}$ concentration to facilitate the analysis for sectoral pollution contributors and pollution flows along the supply chains. To comprehensively represent the environmental impacts of all analyzed pollutants in this study, we introduce the index APE. APE is designed by China's Ministry of Environmental Protection and has been used in many previous studies[52–54]. It enables us to integrate the severity of air pollution caused by multiple pollutants by assigning them a coefficient according to their environmental and health impacts. APE could be calculated as:

$$APE = \sum_{i=1}^{7} \frac{E_i}{R_i} \tag{13}$$

Here, E_i represents the emission of air pollutant i; R_i represents the conversion coefficient of pollutant i, which is assigned according to its impacts upon the ecological system, toxicity on organisms and the technical feasibility for removal. The coefficients of air pollutants used in this study are listed in Supplementary Table 11.

Export-related $PM_{2.5}$ concentration simulation

The export-related $PM_{2.5}$ concentration is then simulated with the GEOS-chem chemical transport model (v14.0.1). $PM_{2.5}$ species simulated by this study include secondary inorganic aerosols (SIOA) (SIOA, including sulfate (SO_4^{2-}), nitrate (NO_3^-), ammonium (NH_4^+), black carbon (BC), primary organic aerosol (POA), secondary organic aerosols (SOA), anthropogenic dust, natural dust and sea salt. The modeled POA is converted from POC with a POA/POC ratio of 2.1 recommended by GEOS-Chem Wiki (https://wiki.seas.harvard.edu/geos-chem/). Anthropogenic dust represents dusty particles emitted from industrial and transportation activities, while natural dust and sea salt are emitted from natural processes. In this study, we only analyze SIOA, BC, POA and anthropogenic dust for export-related $PM_{2.5}$ concentration. We do not consider changes in export-related SOA concentrations, which are simulated poorly by GEOS-Chem model[55].

We conduct a total of five zero-out simulations (including one baseline simulation and four sensitivity experiments) and the detailed information for our simulations is listed in Table 1. The emissions from MEIC with a horizontal resolution of 0.1° × 0.1° (longitude × latitude) serve as a baseline simulation (all-emissions simulation, which shows the impacts of all anthropogenic and natural emissions on $PM_{2.5}$). Sensitivity simulations are designed by omitting from baseline simulation the export-related emissions in different cases. We simulate China's $PM_{2.5}$ concentration by nested simulations at a horizontal resolution of 0.3125° × 0.25° (longitude × latitude) and at 47 vertical levels between the surface and 0.01 hPa. We conduct nested simulations for January, April, July and October 2017 and treated the mean of the 4 months as the annual mean. Boundary conditions are sourced from corresponding global simulations under the horizontal

Table 1 | Configuration of GEOS-Chem simulations in this study

Simulations	Type	Setting of emissions	Resolution	Met fields
Base	Nested	Including all the emissions	0.3125° × 0.25°	GEOS-FP
I_EX	Nested	Excluding all export-related emissions	0.3125° × 0.25°	GEOS-FP
I_EXEAST	Nested	Excluding emissions driven by export demand of the East Coast	0.3125° × 0.25°	GEOS-FP
I_EXDIR	Nested	Excluding emissions driven by direct export	0.3125° × 0.25°	GEOS-FP
I_EXREGION	Nested	Excluding emissions driven by specific foreign region	0.3125° × 0.25°	GEOS-FP
Base_B	Boundary	Same as Base	2.5° × 2°	MERRA2
I_EX_B	Boundary	Same as I_EX	2.5° × 2°	MERRA2
I_EXEAST_B	Boundary	Same as I_EXEAST	2.5° × 2°	MERRA2
I_EXDIR_B	Boundary	Same as I_ EXDIR	2.5° × 2°	MERRA2
I_ EXREGION_B	Boundary	Same as I_ EXREGION	2.5° × 2°	MERRA2

resolution of 2.5° × 2° (longitude × latitude). We spin up every simulation for a period of time to remove the effects of initial conditions (six months for boundary simulations and ten days for nested simulations). The boundary simulations are driven by the assimilated meteorological field MERRA-2 and the nested simulations are driven by GEOS-FP, the year-specific assimilated meteorological field with higher horizontal resolution. The export-related $PM_{2.5}$ concentration is obtained by differences between the all-emission simulation and each simulation excluding related emissions.

GEOS-Chem simulations of $PM_{2.5}$ have been validated by many studies[25,56,57]. Here we compare $PM_{2.5}$ concentration from the all-emissions simulation to the observation data from China's urban air quality real-time release platform (https://air.cnemc.cn:18007/) (Supplementary Fig. 12) to validate the performance of the model. We select 1470 monitoring stations across China and their spatial distribution is shown in Supplementary Fig. 13. The result shows that the GEOS-Chem performs well on the spatial distribution of $PM_{2.5}$ concentration over China ($r = 0.80$, normalized mean bias (NMB) = 16.0%), especially in population-densely populated areas ($r = 0.89$, NMB = 13.1%).

To better reflect the public exposure to $PM_{2.5}$ pollution, we introduce population-weighted $PM_{2.5}$ concentration to represent our results. The population-weighted average $PM_{2.5}$ concentration of region a could be calculated as:

$$C^a = \frac{\sum_{g=1}^{n} c_g \cdot p_g}{P^a} \tag{14}$$

where g refers to the grid cell of the region a under model resolution; n refers to the number of grid cells in the region a; c_g and p_g represent the $PM_{2.5}$ concentration and population of grid cell g respectively; P^a represents the population of the region a.

Structural path analysis (SPA)

To clarify the interprovincial air pollution transfer driven by international exports, the method SPA is introduced in this study. The SPA method is based on Taylor expansion of the Leontief inverse matrix:

$$(\boldsymbol{I}-\boldsymbol{A})^{-1} = \boldsymbol{I}+\boldsymbol{A}+\boldsymbol{A}^2+\boldsymbol{A}^3+\ldots+\boldsymbol{A}^n \lim_{n\to\infty}\boldsymbol{A}^n = 0 \tag{15}$$

Thus, Eq. (8) could be expressed as:

$$\boldsymbol{E} = \boldsymbol{F}(\boldsymbol{I}-\boldsymbol{A})^{-1}\boldsymbol{Y} = \boldsymbol{F}\boldsymbol{Y}+\boldsymbol{F}\boldsymbol{A}\boldsymbol{Y}+\boldsymbol{F}\boldsymbol{A}^2\boldsymbol{Y}+\ldots+\boldsymbol{F}\boldsymbol{A}^n\boldsymbol{Y} \tag{16}$$

Here, $\boldsymbol{F}\boldsymbol{A}^t\boldsymbol{Y}$ represents the emissions from the t-th production layer (PL^t) driven by final demand $\boldsymbol{Y}$. For instance, when $\boldsymbol{Y}$ refers to the demand to produce electronic equipment, $\boldsymbol{F}\boldsymbol{Y}$ (PL^0) is the direct emissions emitted in the assembly process of this electronic equipment; $\boldsymbol{F}\boldsymbol{A}\boldsymbol{Y}$ (PL^1) is the emissions emitted in the production process of parts needed by the electronic equipment manufacturing; $\boldsymbol{F}\boldsymbol{A}^2\boldsymbol{Y}$ (PL^2) or higher layers are the emissions generated from inputs for manufacturing components of the electronic equipment.

The SPA equations could only measure the direct emissions driven by final demand at each PL (Table 2). To measure the embodied APE flows between adjacent PLs, a mapping approach, which can be seen as an extension of SPA, is applied[58]. The sectoral emission matrix driven by the unit output of each sector could be expressed as:

$$\boldsymbol{Q} = \hat{\boldsymbol{F}}\boldsymbol{L} \tag{17}$$

Here, $\hat{\boldsymbol{F}}$ represents the diagonal of the emissions intensity vector. The element Q_{ij} of $\boldsymbol{Q}$ measures the direct and indirect emissions from sector i driven by the unit output of sector j, so that $\boldsymbol{Q}_{i:}$ (the row vector of $\boldsymbol{Q}$) represents emissions from sector i embodied in all sectors' unit output while $\boldsymbol{Q}_{:j}$ (here we defined the column sum of $\boldsymbol{Q}_{:j}$ as m_j) measures emissions from all sectors driven by the unit output from sector j. Based on this matrix, the emissions flow equations between different PLs are displayed in Table 3.

$E_{ji}^{1\to0}$, $E_{kj}^{2\to1}$ and $E_{zk}^{3\to2}$ in Table 3 represents the emissions flows between adjacent PLs. For example, $E_{kj}^{2\to1}$ measures emissions from all sectors driven by the output of sector k at PL^2 purchased by sector j at PL^1 to meet the final demand of PL^0. Other equations show more detailed emission flows between PLs. For example, $E_{kji}^{2\to0}$ measures emissions from all sectors driven by the output of sector k at PL^2 purchased by sector j at PL^1 to meet the final demand of sector i at PL^0.

However, there are infinite production layers in the expansion formula and under limited computing power, it's impossible for us to trace the supply chains of all layers. We only focus on the first four layers according to previous works[59,60] and the contributions of PL^4 and all prior layers are combined to make a complete view of the entire supply chains.

Uncertainty and limitations

Although we have tried to improve the accuracy of the results, limitations still exist in our estimates.

First, the linked MRIO table is with uncertainties due to the data limitations. We have listed the assumptions and our references in this process in Supplementary Table 12. The customs export data lacks detailed information for the consumption sectors in foreign regions. So we assume that the distribution proportion of sectoral consumption in foreign countries[32,34,37,39] and the ratio of intermediate and final goods[32] with exports from Chinese provinces follows that with exports from the whole nation. This simplification would result in uncertainties in provincial sector-to-foreign sector export flows. To ensure the robustness of our findings, we avoid analyses that would amplify these uncertainties, e.g., tracing specific pollution flow from foreign sectors to provincial sectors. Besides, we use the total export volumes of provincial sectors to adjust the sectoral export matrix in the linked MRIO table[39]. The province-to-country export structure derived from customs data is preserved during this process, which ensures

Table 2 | The direct emissions equations at different PLs driven by final demand

	PL^0	PL^1	PL^2	PL^3
Direct emissions	$D_i^0 = f_i y_i$	$D_j^1 = f_j A_{j:} y_i$	$D_k^2 = f_k A_{k:} A y_i$	$D_z^3 = f_z A_{z:} A A y_i$

Table 3 | Emissions flow equations between different PLs

	→ sector i at PL^0	→ sector j at PL^1	→ sector k at PL^2
sector j at PL^1 →	$E_{ji}^{1\to0} = Q_{:j} A_{ji} y_i$		
sector k at PL^2 →	$E_{kji}^{2\to0} = Q_{:k} A_{kj} A_{ji} y_i$	$E_{kj}^{2\to1} = Q_{:k} A_{kj} A_{j:} y$	
sector z at PL^3 →	$E_{zkji}^{3\to0} = Q_{:z} A_{zk} A_{kj} A_{ji} y_i$	$E_{zkj}^{3\to1} = Q_{:z} A_{zk} A_{kj} A_{j:} y$	$E_{zk}^{3\to2} = Q_{:z} A_{zk} A_{k:} A y$

the reliability of our research. Discrepancies between provincial export values in customs data and those in China's MRIO tables remained within 20% for most provinces, narrowing to approximately 15% for high-export-volume eastern coastal provinces. In addition, the construction of the linked MRIO table necessitates sector mapping between MRIO tables and customs data and discrepancies in sector classification criteria also lead to potential uncertainties in this process[8,34,38,39].

Second, uncertainties of the export-related emissions result from the emission inventories (MEIC and GAINS) and MRIO analysis. For example, the uncertainties of MEIC have been estimated to be 12% for SO_2, 31% for NO_X, 68% for NWVOC and 107% for primary $PM_{2.5}$[61,62] and the uncertainty of MRIO analysis is less than 50%[12]. Meanwhile, we use emission data of 2015 and 2020 to estimate the emission shares among sectors of GAINS in 2017 based on a linear estimation. The uncertainties in the linear estimation for the sectoral emission proportion of GAINS are estimated by conducting alternative interpolation methods. Supplementary Fig. 14 shows that under different interpolation methods, the variations for sectoral emission in the hybrid emission inventory are mostly lower than 1.5%. In detail, the range of variation in sectoral emissions is −0.7–0.7% in NO_x, −0.5–0.5% in SO_2, −0.2–0.6% in CO, −0.8–0.6% in NH_3, −0.3–0.4% in BC, −0.7–0.4% in OC, and −0.7–0.7% in other primary $PM_{2.5}$. In this regard, the linear estimation for sectoral emission proportion of GAINS emission has little impacts on our results.

Finally, GEOS-Chem simulations are unavoidably affected by errors in the representation of atmospheric chemical and physical processes such as the formation of secondary aerosols[63–65]. A full evaluation of model uncertainties is computationally prohibitive. However, the uncertainties may be substantially mitigated as we focus on the differences in concentrations between all-emission simulation and sensitivity simulation rather than the absolute concentration simulated by GEOS-Chem[8]. Besides, our simulations do not consider the export-related change in SOA concentrations, which are simulated poorly by GEOS-Chem model[57]. The performance of the model is observably poor in China compared to data of situ observations (i.e., $R < 0.5$)[66]. The SIOA contribute the dominant share of export-related $PM_{2.5}$ pollution and we believe this defect does not affect the general conclusion.

Data availability

The data that support the findings of this study are available on Zenodo with the identifier https://zenodo.org/records/15575540.

Code availability

GEOS-Chem used here is an open-source model and available at https://geoschem.github.io/. The MATLAB (R2022b) custom codes used for the analysis are available on Zenodo with the identifier https://zenodo.org/records/15575540.

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Author contributions

Jingxu Wang, Peng Liu and Heran Zheng conceived the study. Jingxu Wang led the study. Yu Liu and Heran Zheng provided economic data. Youfan Chen provided provincial NH_3 emissions for detailed sectors. Zhengzhong Liu, Siyi Huang, Haoyu Zhang and Zhongyi Li conducted data curation. Yuanhong Zhao and Lulu Chen helped with GEOS-Chem model configuration. Zhengzhong Liu conducted GEOS-Chem simulations. Jingxu Wang and Zhengzhong Liu analyzed data and wrote the draft. Jingxu Wang, Zhengzhong Liu, Peng Liu, Yu Liu, Mingxi Du, Siyi Huang, Yuanhong Zhao, Youfan Chen, Lulu Chen, Kailan Tian, Haoyu Zhang, Zhongyi Li and Heran Zheng edited and reviewed the paper.

Competing interests

The authors declare no competing interests.

Additional information

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