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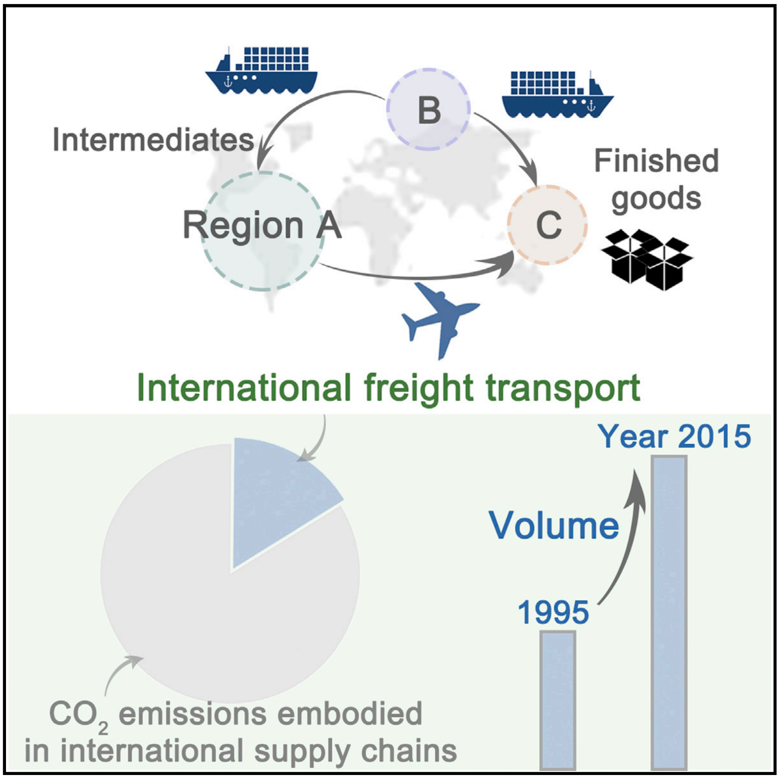
Article

The volume of trade-induced cross-border freight transportation has doubled and led to 1.14 gigatons CO_2 emissions in 2015

Graphical abstract



Highlights

- International freight transport generated 1.14 gigatons CO_2 emissions in 2015
- The volume of international freight transport doubled between 1995 and 2015
- The average consumption-based freight transport distance is 20,000 km

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In brief

The carbon footprint generated by global trade-induced international freight transportation is increasing. Emissions reduction requires effective and targeted policies, but the magnitude of international freight-transport-associated CO_2 emissions and the national and regional contributions remain unclear. Here we fill this knowledge gap by using an updated multi-regional input-output (MRIO) model from 1995 to 2015. Results show that international freight transport generated 1.14 Gt CO_2 in 2015, mainly from Asia (39%), the EU (21%), and the US (13%).

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The volume of trade-induced cross-border freight transportation has doubled and led to 1.14 gigatons CO_2 emissions in 2015

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SCIENCE FOR SOCIETY International trade is vital to global development, but the transportation of goods between regions and countries—be it via railway, shipping, or aviation—all generate CO_2 emissions. These emissions, associated with the transportation of goods, or "freight," must be reduced in order to meet net-zero emissions targets, but the volume of these emissions and the trading partners responsible for them remain unclear. Furthermore, these emissions are not presently covered by the Paris Agreement. In order to achieve net zero and design effective and viable mitigation strategies, these gaps in our knowledge must be filled. Through linking transportation (and the associated emissions) along global goods value chains to the countries and regions that consume the goods, we find that in 2015 international freight transport generated 1.14 gigatons (Gt) of CO_2 emissions. Between 1995 and 2015, Asia, the EU, and the US were together responsible for nearly three-quarters of the trade-induced transport carbon footprint. Tailor-made responsibility-sharing mitigation strategies are urgently needed to alleviate the CO_2 emissions of transportation for global trade.

SUMMARY

International freight transport associated with global trade generates significant CO_2 emissions, which are expected to increase with further globalization. The reduction of these emissions will require international and interregional collaboration. However, which trading partners are responsible for freight transport carbon footprints throughout global value chains remains unclear. Here we link bilateral trade flows of export volume to a multi-regional input-output model to measure CO_2 emissions of international freight transport from 1995 to 2015. We find that in 2015, international freight transport generated 1.14 gigatons of CO_2, representing 16% of the total emissions associated with international supply chains. Primary contributors were Asia (39%), the European Union (21%) and the United States (13%). During 1995–2015, the cross-border freight transport volume more than doubled due to rapidly growing consumption and transportation of heavier intermediate goods. Our findings provide the information necessary to design targeted mitigation policies for international freight transport.

INTRODUCTION

The ambitious goals established by the Paris Agreement[1] require global states to mitigate climate change by cutting greenhouse gas (GHG) emissions at a society-wide level, and the nationally determined contributions (NDCs)[2] of the 190 parties to the Agreement thus far reveal their determination and willingness to primarily reduce carbon emissions based on the latest science. The transport sector, which is responsible for one-fifth of global CO_2 emissions,[3,4] has attracted increasing attention worldwide. Policies designed to achieve climate targets also limit emissions originating from transportation and include the implementation of major projects and goals to achieve sustainable mobility. The EU Climate Action Regulation (CAR)[5] sets annual reduction targets for the transport sector, including road transportation, domestic shipping, nonelectric railways, pipelines, and off-road transportation. Domestic aviation has been included in another regulation, the EU Emission Trading System (ETS), since 2012.[6] Automotive fuel economy standards targeting the emissions of passenger cars and trucks in the United States were implemented in 2012.[7] However, international shipping and aviation have remained outside the scope of the Paris Agreement, although they have been considered by international United Nations agencies.

The well-formed goals set by the International Maritime Organization (IMO) (i.e., reducing the carbon intensity of international shipping by 40% by 2030 below the 2008 level[8]) and the International Civil Aviation Organization (ICAO) (i.e., achieving carbon neutral growth from 2020 and reducing carbon emissions by 50% over the 2005 level by 2050[9]) enable member states to consider their international transport-related environmental impacts.[10–15] Although attempts have been made to reduce international transport-related emissions not previously considered in national targets, the identification and regulation of such emissions remain at the initial stage. At the end of 2020, the Marine Environment Protection Committee (MEPC) of the IMO agreed to a draft of a new global enforceable regulatory framework that would provide various technical and operational carbon reduction measures targeting all ships to reduce carbon intensity.[16,17] However, there remains plenty of room to traverse between international and domestic transport-related emissions and to produce a reliable international transport-related emissions inventory based on which specific targets regarding emissions cuts can be determined. Although the fourth IMO GHG study report in 2020 adopted a new voyage-based allocation method to distinguish domestic shipping-related emissions from international emissions using automatic identification system (AIS) data,[18] related strategies with regard to reducing emissions originating from international shipping did not contain clear national contributions and responsibilities and, instead, proposed a worldwide standard.[17,19,20] The Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), which was agreed upon by states worldwide on a voluntary basis and took effect in 2021, requires each state to be responsible for the emissions discharged by its own airplane operators.[9] The IMO and ICAO requirements under the nondiscriminatory guiding principle apparently fail to follow the principle of common but differentiated responsibilities proposed by the United Nations Framework Convention on Climate Change (UNFCCC).[1]

International freight transport, which contributes more than 90% of the emissions originating from shipping[18] and nearly 20% of aviation-related emissions,[21] has become increasingly essential partly due to globalization. No country in this globalized world cannot entirely meet the demands of its citizens without imports such as necessary raw material resources and high-tech components to be assembled. The question of whether emitter-based measures could result in more serious international transport-related carbon leakage, especially trade-related emissions, remains difficult to answer because consistent restrictions can hardly be imposed in all states simultaneously.[22] Sharing the responsibility for international trade-related emissions is likely to become an emerging controversial issue among producers and consumers because carbon emissions may potentially increase quickly,[18,23–26] due to the deepening of globalization, abatement policies in other sectors, and communal pressure to achieve climate goals. Although a number of studies[27–33] have investigated consumer responsibilities by calculating consumption-based emissions, the emissions generated during international transportation have not been well linked to consumption because sector-specific emission intensities remain the same for different foreign traders. In a consumption-based analysis, the foreign and domestic consumption of the same kind of product should not be regarded as the same. The emissions from international freight transport are significantly different depending on the transport modes and distances.[34,35] Cristea et al.[36] calculated the GHG emissions from international transportation in 2004 and compared them with those from output. Cadarso et al.[37] proposed a methodology for measuring broad consumption responsibility (BCR, including "both the pollution related to demand for domestic and imported goods and emissions from the international transport of those imports") and calculated Spain's responsibilities in 2000. However, the analysis of the total (direct and indirect) impacts of consumption in various regions on the level of international freight transport and its emissions in the global context remains limited.

Here we provide the total linkage between international freight transport (excluding domestic transport) and consumption along the global value chains from 1995 to 2015 by linking bilateral trade flows in weight with a global multi-regional input-output (MRIO) model, and we estimate destination-specific CO_2 emissions based on the level of international freight transport. A new indicator, consumption-based freight turnover (CFT, a spatial and general concept of the material footprint), is introduced to reflect the total (direct and indirect) international freight turnover volumes driven by the final consumption of an economy. We further define the average CFT as the intensities of CFT or the equivalent distance to measure the distance that one-unit weight of material travels when one-unit weight of finished goods is consumed. Results show that in 2015, approximately 1.14 gigatons (Gt) CO_2 from international transport accounts for 16% of the emissions in international supply chains. Between 1995 and 2015, the cross-border freight transport volume more than doubled due to rapidly growing consumption and transport of heavier intermediate goods. In 2015, 63% of traded goods were mineral products. On a global average, each ton of final consumption in 2015 required a cross-border freight turnover of 20,000 ton-km (equivalent to 1 ton of goods traveling a hemispheric-scale distance), which is generated by the goods from the entire supply chains. The findings provide new perspectives for defining regional responsibility for reducing international freight transport emissions as well as for developing tailor-made (e.g., common but differentiated) mitigation policies.

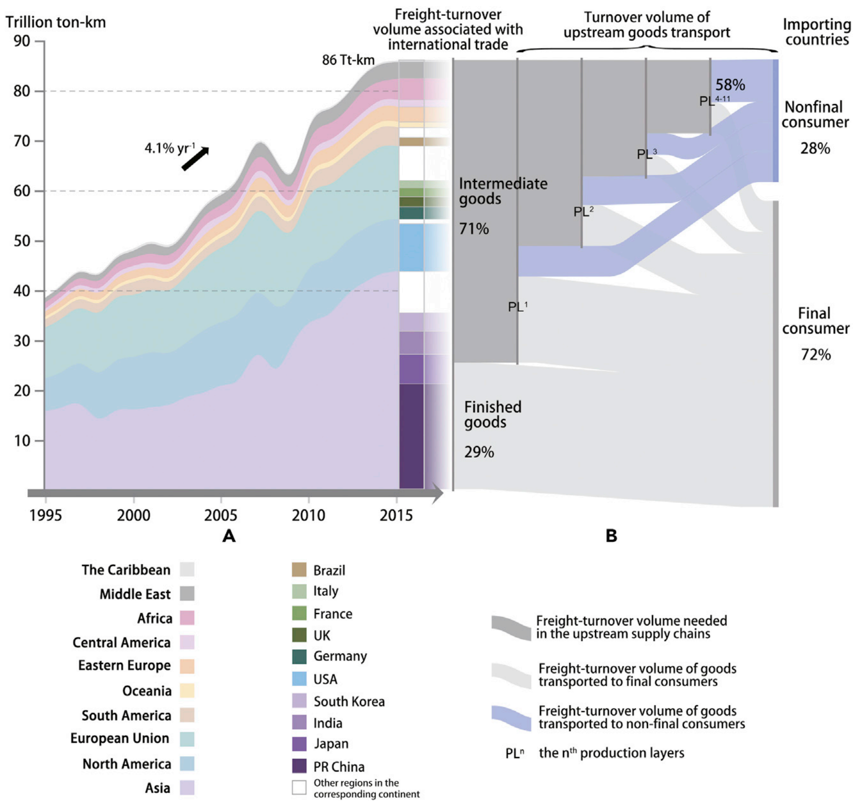

Figure 1. Consumption-based freight turnover (CFT) volume associated with international trade

(A) Freight turnover in regions worldwide from 1995 to 2015 (unit: ton·km; CFT is designed to estimate the driving forces of final consumption by tracing both direct imports to final consumers, excluding imports driven by the final consumption in other countries, and the indirect trade of intermediate goods transported to nonfinal consumers).

(B) Sankey plot of the gross freight turnover in 2015 further distinguishing traded goods transported to final and nonfinal consumers. The width of the flows is proportional to the magnitude of the turnover volume. Production layers consist of the goods transported to nonfinal and final consumers. The rightmost flows of PL^{4-11} represent the totals of flows from the rest of the production layers (from PL^4 to PL^{11} because our study considers up to 11 production layers, which can ensure that results account for more than 99% of global supply chains).

RESULTS

Consumption-based international freight turnover

Over the span of two decades (1995–2015), the international trade-related freight turnover volume more than doubled, probably driven by the uneven distribution of resources and growing specialization worldwide (detailed results are available in Data S1).[36,38–41] The annual average growth rate was as high as 4.1% per year. In 2015, the global volume amounted to 86 trillion metric ton-km in absolute terms. The global freight turnover overcame a brief drop in the 2008–2009 period and persisted along its high-growth trajectory in the long run, indicating not only rapid growth in the international trade volume but also an unprecedented degree of interdependence among countries in a globalized world.

The CFT results for the various regions are shown in Figure 1. During this period, the CFT of the developing countries tended to increase at a high rate. The emerging economy of PR China had the highest growth rate, 14% per year on average between 1995 and 2015, and it accounted for the largest absolute volume (21 Tt-km) in 2015, thereby notably increasing the global freight turnover volume. India was not far behind and achieved a growth rate of 10% per year. Eastern Europe and the Middle East achieved a growth rate of 6% per year. In contrast, relatively weak growth or even a slight decline was observed in developed regions—for example, 2% per year in the United States, 1%–3% per year in four member states (as shown in Figure 1) of the EU (Data S2, Sheet 1) and −1% per year in Japan. Although they did not have outstanding growth, the United States (10 Tt-km) and Japan (6 Tt-km) accounted for a substantial portion of the global freight turnover in absolute terms (Figure S1). Interestingly, PR China rapidly developed and even surpassed these countries after the 2008–2009 global financial crisis, resulting in a slump in their turnover. The shares of the CFT of the US and Japan declined significantly after 2005: the share of Japan dropped from 11% to 7%, while the share of the US dropped from 20% to 11%.

Notably, freight turnover is mainly associated not with finished goods but with intermediate goods (detailed data pertaining to various regions are available in Data S2, Sheet 2). Intermediate goods[37] are goods that are consumed as inputs in the production of other goods including final/finished goods. Finished goods[42,43] are goods that are ready for sale and purchased by final consumers (end users) for their own use. The colors indicate the turnover volume attributed to the final consumers in each region/country. Most existing studies show that the trade in intermediates plays a key and increasingly important role in international trade.[44–48] We found that, in general, the freight turnover volume of intermediate goods was three times as large as that of finished goods in 2015, which suggests that three-quarters (71%) of the global trade-related freight turnover was needed upstream to support the production and consumption of finished goods. It is worth noting that the distinction between intermediate and finished goods does not depend on the form of the product but on how the purchaser uses it. Intermediate goods are used as inputs, while finished goods are purchased by final consumers (end users) for their own use. Indirect trade (referring to the trade of intermediate goods transported to nonfinal consumers) accounted for nearly one-quarter of the total turnover, playing a necessary role in the production of finished goods finally exported to and consumed by final consumers. Moreover, in the upstream of supply chains, indirect trade becomes increasingly important, and it could account for even half (58%) of the turnover volume in the most remote link

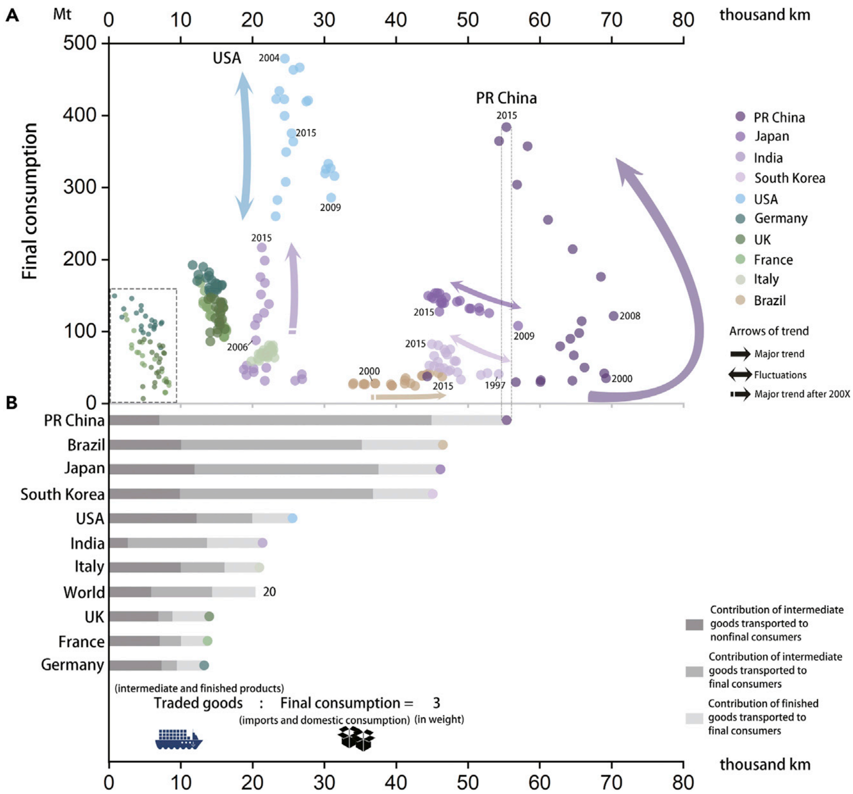

Figure 2. Annual equivalent distances embodied in each ton of final consumption of the selected nations

(A and B) The equivalent distance is calculated as $\frac{CFT}{\textit{final consumption (in weight)}}$, representing the average freight turnover driven by final consumption, which is equivalent to the distance traveled by 1 ton of material when 1 ton of finished goods is consumed.
(A) Amount of final consumption and the corresponding equivalent distances of the selected countries from 1995 to 2015. (B) Contributions of the three subdistances and ratio of the traded goods to final consumption in 2015. The CFT is divided into three parts based on the different stages in global supply chains, and, thus, the three corresponding subdistances can be calculated. Detailed results for all regions are provided in Data S2 Sheet 3, and those for other years are provided in Data S4.

(production layers [PL]$^{4-11}$, representing the transport of intermediate goods after the 3rd layers).

Equivalent distances driven by final consumption

Freight turnover (measured in tons-km) depends on the weight of transported goods (in tons) and the traveling distance (in km). Intuitively, CFT is determined as the product of the weight of traded goods (including goods for final consumption and intermediate inputs) and the distance between bilateral traders. The average distance ($\frac{CFT}{\textit{traded goods (in weight)}}$) reflects the average distance traveled by cargo (the results are available in Data S3). In contrast to the traditional concept, the equivalent distance ($\frac{CFT}{\textit{final consumption (in weight)}}$) measures the driving forces of the final consumption of a given region. Since cargos as intermediate inputs are finally processed into finished goods, from a consumption perspective, CFT does not occur except for final consumption. CFT can be regarded as a generalized material footprint because it takes into account processed goods (both intermediate and final goods) instead of raw materials. In contrast, the material footprint considers only raw materials. In addition, CFT reflects the movement of materials that have undergone a first processing step. Compared to the traditional material footprint, CFT can also be regarded as a kind of mobile and spatial material footprint. In fact, the equivalent distance represents the intensity of CFT. It is calculated as the average freight turnover driven by a one-unit weight of final consumption, which is equivalent to the distance traveled by 1 ton of goods when 1 ton of finished goods is consumed.

We selected ten countries with relatively large turnover volumes to further analyze how their turnover changed over this period. We found two typical trends of change: a major trend and fluctuations (arrows in Figure 2). The trend in PR China is remarkable, with final demand remaining almost constant until 2000 but increasing significantly after 2008. The Chinese equivalent distance reached a record high of 70,000 km in 2008 and experienced a progressive decline thereafter, but its negative impacts on turnover were completely offset by a very large increase in the final demand. India and Brazil show clear but quite different trends after 2006 and 2000, respectively. India's final demand rose significantly after 2006, but the equivalent distance remained almost unchanged. In contrast, the final demand in Brazil remained almost unchanged, but the equivalent distance increased after 2000. However, countries with relatively mature economies do not show a clear trend of change. In the United States, for example, there is no clear pattern, although final demand varied considerably. The change in the final demand of Japan and Korea was not as pronounced as the change in their equivalent distances. European countries were rather similar, with an equivalent distance of approximately 15,000 km. In addition, the changes in their final demand were also less significant.

On a global average, in 2015, 1 ton of final consumption (including imports and domestic consumption) drove an international freight turnover of 20,000 ton-km. From the equivalent distance perspective, 1 ton of goods traverses approximately 20,000 km (half of the terrestrial globe), accompanied by potential environmental impacts. Over a two-decade span, the average equivalent distance grew gradually and with fluctuations from 16,000 km (Figure S2A). The hemispheric-scale nature of international trade has enlarged the scale effect of cross-border final consumption and has exerted pressure on international freight turnover. The equivalent distances of most East Asian countries have almost doubled the global level, contributing to a higher CFT with increasing final consumption. Given the same modal shares and emission intensities, the longer the distance embodied per unit weight of final consumption, the more potential CO_2 emissions are discharged into the atmosphere or the greater other potential environmental impacts are.

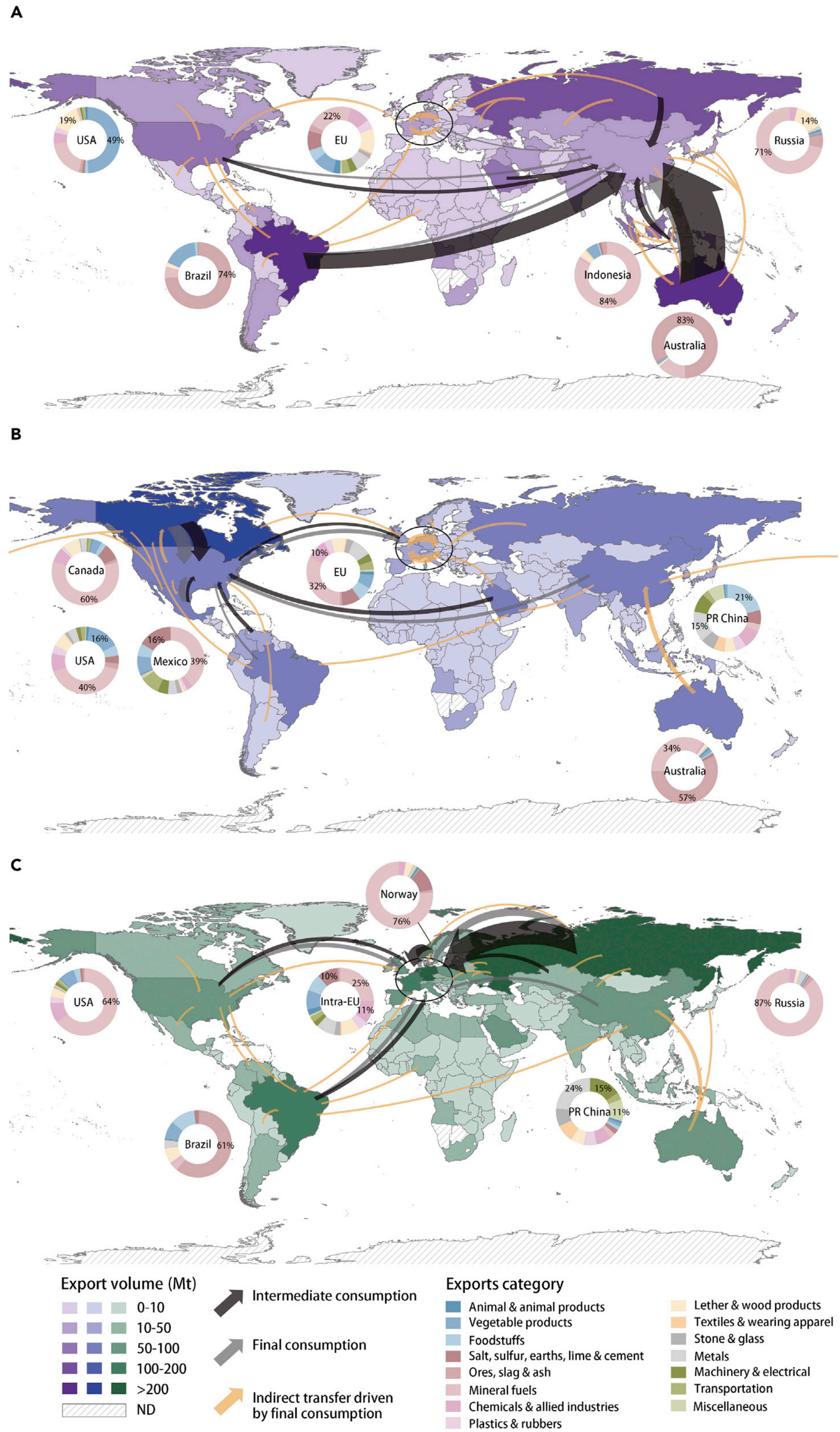

Figure 3. Largest interregional fluxes of traded goods (Mt) in 2015 driven by final consumption in key regions

(A–C) (A) Trade flows driven by final consumption in PR China; (B) trade flows driven by final consumption in the United States (USA); and (C) trade flows driven by final consumption in the European Union member states (EU-28). The shading indicates the amount of exports of each country (in weight). The arrows in each

(legend continued on next page)

The hemispheric-scale nature of international trade results from the fact that final consumption drives three times the weight of transported goods in bilateral trade (time-series data are shown in Figure S3). In 2015, 67% of internationally traded goods consisted of intermediate goods (in weight). By product categories, 43% of internationally traded goods consisted of mineral fuels, and 14% consisted of ores, slag, and ash (Figure S4). Abundant high-weight but low-value-added intermediate goods are needed upstream to be further processed into finished goods and to meet cross-border demands. If production sites are located near intermediate input suppliers, the avoidable trade volume associated with intermediate goods can be minimized, and thus upstream supply chains can be optimized.

CFT takes into consideration all the upstream freight transport turnover along the global supply chains that is driven by total final consumption. Upstream freight transport can be categorized based on the different stages of supply chains: intermediate goods imports and finished goods imports. Intermediate goods imports can further be classified into the imports to final consumers and imports to other regions. Correspondingly, the transported goods can be divided into three types, namely, intermediate goods transported to final consumers and to nonfinal consumers (other regions) and finished goods transported to final consumers. The transport turnover of the three kinds of goods divided by final consumption equals the equivalent distances of the goods (three subdistances), representing the average freight turnover driven by final consumption.

The contributions of these three subdistances can be considered to reflect the patterns of the upstream supply chains of a region's final consumption. In most regions or countries, the subdistances of intermediate goods account for the majority of the equivalent distance, reflecting the fact that much more indirect freight turnover is driven than the direct freight turnover of finished goods. In addition, the contributions of the intermediate goods transported to final consumers reflect the degrees of involvement in the upstream supply chains. For example, the intermediate goods transported to PR China account for 68.5% of its equivalent distances. Regarding the US, 30.5% is attributed to the intermediates transported to itself, while 47.6% is associated with the intermediates transported to other countries. PR China is highly involved in its own consumption-driven upstream chains.

We also found that the patterns of the upstream supply chains of a region's final consumption changed from 1995 to 2015. Although the total equivalent distance of most countries did not vary much, the contribution of indirect trade (intermediate goods transported to nonfinal consumers) changed (Figure S5 and Data S4). As for Japan, the share of indirect trade doubled between 1995 and 2015. It was also found that after growth, a downward trend occurred in the contribution of the indirect trade of certain countries, such as the United States, PR China, South Korea, and India. A larger share of indirect trade typically reflects the complexity of supply chains, involving multiple suppliers and producers worldwide. Complex global supply chains complicate the task of assigning emission mitigation responsibilities.

Patterns of interregional trade driven by key consumers

To gain a deeper understanding of the reasons for the differences in CFT and the equivalent distance, we identified the transported goods and their origin. The results of interregional trade driven by selected important consumers, namely, PR China, the United States, and the EU-28 countries, are shown in Figure 3 (detailed trade flows are available in Data S5).

All three final consumers conduct trade with one or two of the most important exporters, accounting for a considerable proportion of their imports and supplying primarily semifinished goods. In addition, the import structure of each region is dominated by mineral products, such as mineral fuels, ores, lime, and cement. In regard to PR China, Australia exports ores, slag, and ash in large quantities. Canada and Venezuela mainly export mineral fuels to the US. Russia is the largest exporter of mineral fuels outside the EU-28 countries.

Compared to the US and EU-28 countries, the geographical location of PR China, which is distant from material sources, partly led to its longer freight transport distance. Compared to the US (8%), ores, slag, and ash accounted for a larger proportion (42%) of flows driven by China (Figure S6), mainly originating from Australia and Brazil. The mineral fuels driven by PR China, accounting for 34%, largely came from Russia and Indonesia, while mineral fuels accounted for 49% of the flows driven by the US, the same as those of PR China in absolute terms (0.7 Gt), with closer important sources (Canada and Venezuela). For the EU-28 nations, half of the transported goods by weight were traded among EU-28 member states (intra-EU trade). In addition, as the largest external exporter, Russia is adjacent to the EU-28.

Indirect trade flows offer a general picture of the far-reaching impacts of a region's final consumption. To satisfy foreign demand, exporters may require upstream imports, the transport of which may cause a vast amount of freight counterflow. The final consumption of the US drove massive exports to Canada (31 Mt) and Mexico (24 Mt). Furthermore, along the upstream supply chains of the US' final consumption, exports from the US accounted for more than 65% of Canada's and Mexico's total imports. Repeated transport could lead to an additional increase in freight turnover and thus could yield more adverse impacts on the environment.

CO_2 emissions from international freight transport

Previous studies have examined carbon leakage issues and calculated consumption-based emissions directly with the Leontief inverse matrix. Davis and Caldeira[27] estimated that in 2004, 23% of global CO_2 emissions (6.2 Gt) were associated with international trade, including emissions from freight transport. However, common usages of the Leontief inverse matrix fail to separate out cross-border transactions from global value chains (details are available in the supplemental information). Our study considers all the cross-border trade driven by the final consumption and calculates total (excluding the domestic trade-related emissions) and transport-related CO_2 emissions. In addition, we estimate the embodied CO_2 emissions based on the emission intensity

panel indicate the imports and exports of the dominant exporting countries, including black and gray flows to final consumers (the width reflects the weight of the goods transported) and orange flows to nonfinal consumers. The fluxes to and from the EU are aggregated (simple summation) to include 28 countries (Table S1). The pie charts detail the product structure (detailed product categories are provided in Table S2) of exports from important exporters to final consumers (including intermediate and final consumption).

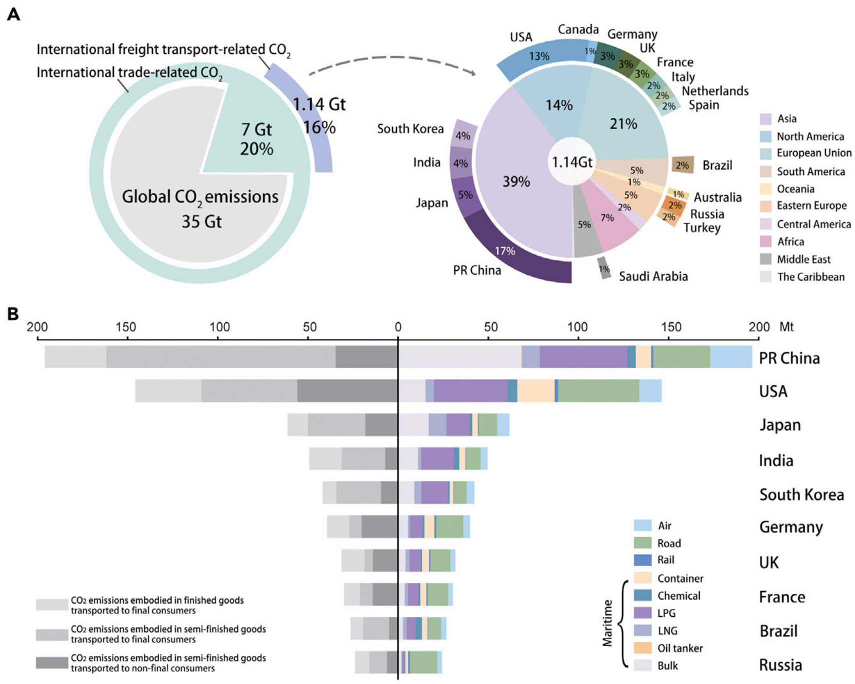

Figure 4. CO_2 emissions embodied in international trade-related freight transport in 2015

(A) Contribution of international trade-related emissions and freight transport-related CO_2 emissions driven by global regions' final consumption. Global and international trade-related CO_2 emissions include all anthropogenic sources (excluding land use, land-use change, and forestry [LULUCF], as provided in Table S3) provided by the Eora database. A comparison of the international trade-related and freight transport-related CO_2 between selected countries is shown in Figure S7.

(B) Contributions of the three stages of supply chains and different transport modes to the CO_2 emissions emitted along global supply chains.

(g/ton-km), considering the effects of CFT without accounting for energy efficiency improvement over time.

We found that in 2015, approximately 1.14 Gt CO_2 emissions (accounting for 3.2% of the global total anthropogenic CO_2 emissions, at 35.21 Gt)[49] originated from fossil fuels burned in the road, rail, air, and marine environments in international trade-related freight transport. As shown in Figure 4A, 16% of international trade-related CO_2 emissions could be attributed to international freight transport. International trade-related CO_2 emissions are calculated by summing up all the emissions (from energy use, industrial processes, agriculture, etc.) associated with the goods transported internationally (Figure 5). For example, the international trade-related CO_2 emissions of an imported computer include not only emissions from transporting the computer and its intermediate inputs, but also emissions from manufacturing the computer and processing its intermediate goods. On a global average, 1 ton of finished goods caused an estimated 0.27 tons of CO_2 originating from freight transport. The amount of embodied CO_2 in each region's CFT is largely determined by intermediate goods transport (to final and nonfinal consumers), accounting for more than 50% in most regions. However, the shares of the transport to nonfinal consumers (0.2%–80%) vary greatly (Data S6).

In terms of the modal shares, shipping was responsible for approximately 90% of the freight turnover to serve cross-border or cross-continent trade[34] because heavy bulk commodities that travel long distances are likely to be carried by sea. Shipping undoubtedly contributed the majority of transport-related CO_2 emissions in international trade. However, contributions of the various submodes of shipping exhibited different patterns mainly due to varying import structures. The United States drove mainly mineral fuels, while PR China drove a large number of mineral fuels, ores, slag, and ash (Figure S6), and these goods were likely transported in bulk carriers.[34]

DISCUSSION

Over a 20-year period, international freight turnover more than doubled, accompanied by an increase in the average volume of turnover driven by final consumption. International freight transport-related CO_2 emissions may continue to increase due to the deepening of globalization, which consequently may weaken the massive efforts being made to meet climate targets under the nondiscriminatory principle. Based on the traditional consumption-based approach, the emissions generated during international transportation cannot be well linked to consumption because sector-specific emission intensities remain the same for different foreign traders. By designing two indicators, CFT and the equivalent distance, we provide a new perspective on and deeper insight into the patterns and main causes of transport-related emissions. The effects of final consumption on international freight transport as well as related CO_2 emissions vary considerably among regions, and in this regard, our results can provide additional support for international cooperation to reduce CO_2 emissions. Our study is subject to methodology limitations and uncertainties in several factors: the MRIO model, structural path analysis (SPA) limitations, traveling distance data, and estimated CO_2 emission factors (a detailed analysis is provided in the supplemental information). In addition, the freight turnover does not consider empty running, which also accounts for any trade-related transport and leads to adverse environmental impacts. Except for CO_2, shipping also emits abundant black carbon (BC), sulfur oxide (SO_x), nitrogen oxide (NO_x), and other pollutants, thus affecting climate change simultaneously. In the future, relevant analyses of the influences of trade-related freight transport will be continuously improved based on more complete data.

More collaborative efforts should be made to control and mitigate international trade-related CO_2 emissions. Current mitigation measures mainly control pollution at its sources (such as the deployment of cleaner ships). However, as suggested by Liu et al., the trade volume should be optimized by

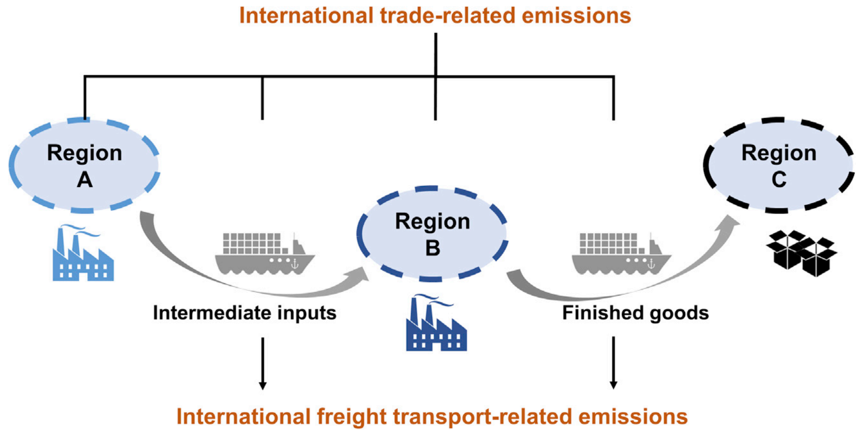

Figure 5. Illustration of the concept of international trade- and international freight transport-related emissions

reducing the avoidable trade and improving the trade structure (for instance, reducing low-value-added and high-weight commodities in trade and avoiding empty ships on return).[50] On a global average, 1 ton of final consumption requires the transport of 2.8 tons of intermediate goods and 0.7 tons of finished goods. The majority (60%) of the international freight turnover in bilateral trade is associated with low-value-added but high-weight goods (mineral products).[51] If these heavy cargos could be further processed to a certain degree before export, a cascade of freight turnover-related and potential environmental impacts (such as CO_2, BC, SO_x, and NO_x emissions) could be avoided. In addition, whether there is room for a further decline in the gradually increasing average turnover warrants further investigation. If the international freight turnover driven by one unit of final consumption can be lowered and the efficiency of international trade can be enhanced, then such changes will help to cut CO_2 emissions.

International freight transport-related CO_2 emissions should be further measured and refined as an essential basis for more detailed policy development. At present, the IMO distinguishes between international and domestic shipping based on AIS data.[18] Liu et al. evaluated the US-PR China bilateral trade-related emissions and corresponding health impacts based on AIS data.[52] Stojanovi'c et al. proposed a macrologistics responsibility approach to allocate responsibilities for CO_2 emissions from international trade-related transport.[53] Oberschelp et al. quantified global emissions for coal-generating units including those along transport routes, which focused on specific supply chains.[54] It is important to investigate whether there exists a suitable bottom-up approach to capture the life cycle of goods, provide more useful information on the allocation of emission mitigation responsibilities, and pay more attention to achieving climate targets in the post-Paris Agreement era.

In the future, international trade patterns will continue to change due to many factors after 2015. In particular, due to the COVID-19 pandemic, there are increasing predictions and analyses about whether value chains will be globalized or deglobalized in the future. Miroudot[55] concluded that there is no evidence that complex supply chains are more affected by COVID-19. Arriola et al.[56] suggested that "localizing value chains in the post-COVID world would add to the economic losses" and that "the international network of interconnected supply chains remains key to producing essential goods and services." The globalization trend will be known only after a longer period of time.[57] As Demirova et al.[58] stated, international trade will run its course through booms and busts. The United Nations Conference on Trade and Development (UNCTAD) also reported that global trade in 2021 had substantially rebounded from 2020 and that its value was even higher than that in 2019. Although our findings may not fully capture the trade patterns in the post-COVID-19 world, international trade and its transportation should be taken seriously to address global environmental issues to meet the goals of deep carbon mitigation and global carbon neutrality in the near future.

Persistent ignorance of the fact that the ambition to reduce international transport-related emissions is falling behind similar efforts in other sectors[1,24] may offset global efforts to achieve carbon neutrality and climate targets. Increasing freight transport demand and more ambitious global emission reduction goals will certainly put pressure on all parties to achieve a technological breakthrough. From a consumption perspective, the one-size-fits-all approach (globally standardized mitigation requirements) no longer works, and gradual steps toward equitable mitigation can be further investigated in the future.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and requests for resources and reagents should be directed to and will be fulfilled by the lead contact, Junfeng Liu (jfliu@pku.edu.cn).

Materials availability

This study did not generate new unique materials.

Data and code availability

The Eora global supply chain database is adopted in this work (Eora 26, available on the web at www.worldmrio.com) because it provides a complete time series of high-resolution MRIO tables, better matching the resolution of the exports volume database (the CEPII-BACI database, available at www.cepii.fr). The CEPII-BACI database, retrieved from the United Nations Comtrade Database, provides detailed trade flows in both value and weight accompanied by information on exporters, importers, product items, and years, which enables us to calculate varying ratios for the different traders, traded goods, and years. The travel distances considered are obtained from two databases: CEPII-GeoDist (available at www.cepii.fr) and the CERDI-sea distance database (available at Zenodo: https://doi.org/10.5281/zenodo.240493). Regarding roads, railways, and aviation, we adopt the simple distances reported in the CEPII-GeoDist database, calculated following the great circle formula. Regarding seaborne transport, we apply the bilateral maritime distances reported in the CERDI-sea distance database to avoid notable underestimation of the actual hauling distances. When estimating the freight turnover under the different transport modes, we rely on the regional modal shares in kg-km given by Cristea et al.[34] and reported shipping and aviation freight turnover volumes. The CO_2 emission factors applied in this work are derived from Cristea et al.[34]

for the shipping, road, and rail environments, and the aviation factor is obtained from McKinnon and Piecyk.[59]

The supporting information and all the datasets cited in the text have been deposited at Zenodo: https://zenodo.org/record/7111061#.YzJqh0xBxEY and are publicly available. The calculations were processed in MATLAB 2020b. All computer codes generated during this study is deposited to Zenodo: https://zenodo.org/record/7114936#.YzJqmkxBxEY.

Calculations of the CFT and emissions

We calculated the CFT of regions on the basis of the exports volume (in weight) in the CEPII-BACI,[51] monetary transactions in the Eora, and the travel distances.[60],[61] First, according to the product concordance (H92 to ISIC Rev 3),[62] we deleted the unmatched products/sectors in the BACI and the Eora (Tables S4 and S5). Second, with the use of the SPA,[63] we captured the production-layer-based upstream intermediate demands of each region. Third, we obtained intermediate demands in weight by segmenting the overall exports volume according to the percentage of consumption-based monetary transactions. Then the CFT can be calculated by multiplying intermediate demands in weight by the travel distances. The CFT of region j can be calculated as follows:

$$CFT_j = PL_j \Big/ \sum_j^M PL_j \times Q \times D_w \quad \text{(Equation 1)}$$

where PL_j represents the trade flows driven by the final consumption in region j (in value, dollars); $\sum_j^M PL_j$ is the total trade flows (in value, dollars) driven by M regions (all the regions); Q is constructed on the basis of the CEPII-BACI database and represents total international trade flows (in weight, tons); and D_w is the weighted transport distances (km). Detailed calculating formulas of PL_j and are provided in Equations 7 and 8.

We further classified the CFT by importing regions and production layers to estimate the freight turnover of intermediate goods to nonfinal consumers and final consumers and the freight turnover of final goods.

The CO_2 emissions discharged from the CFT of region j are estimated as follows:

$$E_j = ef_t \sum_t CFT_{jt} \quad \text{(Equation 2)}$$

where ef_t is the CO_2 emission factor (g/t-km) of transport mode t (shipping, aviation, roads, and railways, Table S6). Sub-turnover volumes CFT_{jt} by shipping, aviation, roads, and railways are estimated according to the modal shares.

Methodological improvements and limitations

Previous studies have calculated consumption-based emissions directly based on the Leontief inverse matrix as follows[64]:

$$E = e(I - A)^{-1} Y \quad \text{(Equation 3)}$$

where e is the direct emission intensity, representing the sectoral emissions per unit total output, I is the identity matrix, A is the direct requirement coefficient matrix, $(I - A)^{-1}$ is the Leontief inverse matrix, tracking the overall direct and indirect upstream inputs along the supply chains, and Y denotes the final consumption. With the use of Taylor series approximation,[63] the equation above can be expressed as follows:

$$E = eIY + eAY + eA^2Y + eA^3Y + \cdots + eA^{\infty}Y \quad \text{(Equation 4)}$$

Element E_{ij} of E indicates the emissions discharged by sector i to finally meet the production requirements of sector j.

However, the result includes both domestic trade and cross-border trade. Moreover, using existing common methods cannot separate out the cross-border trade along the global value chains. Two common approaches to calculating international environmental impacts are setting the diagonal elements of E as zero and setting those of Y as zero. Then we explain in detail why these methods are not adopted in our study.

First, the diagonal elements of E are set as zero. For example, if considering the monetary transactions among three regions, the first production layer can be expressed in matrix form as follows:

$$PL_1 = eAY = \begin{bmatrix} e_1 & 0 & 0 \\ 0 & e_2 & 0 \\ 0 & 0 & e_3 \end{bmatrix} \times \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \times \begin{bmatrix} y_{11} & y_{12} & y_{13} \\ y_{21} & y_{22} & y_{23} \\ y_{31} & y_{32} & y_{33} \end{bmatrix}$$
$$= \begin{bmatrix} e_1 \sum_{n=1}^3 a_{1n}y_{n1} & e_1 \sum_{n=1}^3 a_{1n}y_{n2} & e_1 \sum_{n=1}^3 a_{1n}y_{n3} \\ e_2 \sum_{n=1}^3 a_{2n}y_{n1} & e_2 \sum_{n=1}^3 a_{2n}y_{n2} & e_2 \sum_{n=1}^3 a_{2n}y_{n3} \\ e_3 \sum_{n=1}^3 a_{3n}y_{n1} & e_3 \sum_{n=1}^3 a_{3n}y_{n2} & e_3 \sum_{n=1}^3 a_{3n}y_{n3} \end{bmatrix}$$
$$= \left[e_i \sum_{n=1}^3 a_{in}y_{nj} \right] \quad \text{(Equation 5)}$$

where $a_{in}y_{nj}$ is the input from region i to region n to satisfy the final demand of region j for the outputs of region n. For $i = j$, the emissions $e_i \sum_n^3 a_{in}y_{ni}$ are regarded as a local environmental impact, representing the emissions of region i driven by its own consumption. However, the trade volume (in value) it contains is not only domestic trade. When $i = j$ and $n \neq i$, for example, $a_{12}y_{21} + a_{13}y_{31}$ represents the exports from region 1 to region 2 and to 3. This part is further estimated as local environmental impacts because $e_1a_{12}y_{21} + e_1a_{13}y_{31}$ represents the emissions discharged in region 1, which also acts as a final consumer. What we can learn from the result of E is that the emitter and the final consumer are clear. Then we set the diagonal elements of E as zero, and the result only includes the emissions from the production abroad. Therefore, if estimations only consider the emissions originating from the production, the method is reasonable.

If estimations consider the emissions originating from international freight transport, the method is infeasible. When e represents the emission intensity from the freight transport, we need to make sure the trade volume (in value) only includes cross-border trade. What about deleting the domestic demand in Y?

Second, the diagonal elements of Y are set as zero. Although we can change the final demand matrix to only consider international final demand, the results still mix up domestic trade and cross-border trade. For example, considering monetary transactions among three regions, the first production layer can be expressed in matrix form as follows:

$$PL_1 = eAY = \begin{bmatrix} e_1 & 0 & 0 \\ 0 & e_2 & 0 \\ 0 & 0 & e_3 \end{bmatrix} \times \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \times \begin{bmatrix} 0 & y_{12} & y_{13} \\ y_{21} & 0 & y_{23} \\ y_{31} & y_{32} & 0 \end{bmatrix}$$
$$= \begin{bmatrix} e_1 \sum_n^{2,3} a_{1n}y_{n1} & e_1 \sum_n^{1,3} a_{1n}y_{n2} & e_1 \sum_n^{1,2} a_{1n}y_{n3} \\ e_2 \sum_n^{2,3} a_{2n}y_{n1} & e_2 \sum_n^{1,3} a_{2n}y_{n2} & e_2 \sum_n^{1,2} a_{2n}y_{n3} \\ e_3 \sum_n^{2,3} a_{3n}y_{n1} & e_3 \sum_n^{1,3} a_{3n}y_{n2} & e_3 \sum_n^{1,2} a_{3n}y_{n3} \end{bmatrix}$$
$$= \left[e_i \sum_{n \neq j}^3 a_{in}y_{nj} \right] \quad \text{(Equation 6)}$$

where Y represents imports demand. For $i = j$, the emissions $e_i \sum_{n \neq i}^3 a_{in}y_{ni}$ are discharged in region i and driven by the local imports. The trade volume it contains is international trade, but the result is different when $i \neq j$. When $i = n \neq j$, for example, $a_{22}y_{21}$ represents the domestic trade within region 2. This part is further estimated as cross-border environmental impacts because $e_2a_{22}y_{21}$ represents the emissions from the production of the intermediate inputs, which are further used to produce the imports of region 1. The result of E cannot separate out international trade volume by excluding domestic final demand in Y. The reason is that the Leontief inverse matrix $(I - A)^{-1}$ includes all the upstream trade, including domestic trade of intermediate inputs.

In addition to the above two common ways to remove the effects of local trade, Cabernard et al.[65] proposed a new method to separate out target-sector-regions by adjusting relative matrixes. We think that this method is also effective in removing local trade and its effects, but it is not applicable to this study because we have a larger number of subjects (the results of each country have to be calculated).

Table 1. The ratios of the sum of 12 production layers to all trade volumes from 1995 to 2015 (unit: %)

Year	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
Ratio	99.71	99.60	99.84	99.87	99.88	99.86	99.86	99.85	99.85	99.84	99.75
Year	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	
Ratio	99.73	99.51	99.40	99.25	99.23	99.22	99.29	99.27	99.44	99.53	

Based on the above analysis, we conclude the following:

- It is feasible to use the Leontief inverse matrix to estimate environmental impacts from the production.
- The results of the two methods above include both domestic trade and international trade.
- The methods above cannot be used to estimate environmental impacts from the international freight transport.

Therefore, we made some improvements to meet our needs.

Our study tracks each cross-border trade by calculating $a_{in}\sum_j y_{nj}$ in each production layer. For example, the three-region first production layer can be expressed in matrix form as:

$$PL_1 = A*Y = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} * \begin{bmatrix} \sum_j^3 y_{1j} & \sum_j^3 y_{2j} & \sum_j^3 y_{3j} \\ \sum_j^3 y_{1j} & \sum_j^3 y_{2j} & \sum_j^3 y_{3j} \\ \sum_j^3 y_{1j} & \sum_j^3 y_{2j} & \sum_j^3 y_{3j} \end{bmatrix}$$

$$= \begin{bmatrix} a_{11}\sum_j^3 y_{1j} & a_{12}\sum_j^3 y_{2j} & a_{13}\sum_j^3 y_{3j} \\ a_{21}\sum_j^3 y_{1j} & a_{22}\sum_j^3 y_{2j} & a_{23}\sum_j^3 y_{3j} \\ a_{31}\sum_j^3 y_{1j} & a_{32}\sum_j^3 y_{2j} & a_{33}\sum_j^3 y_{3j} \end{bmatrix} \quad \text{(Equation 7)}$$

$$= \left[a_{in}\sum_j^3 y_{nj}\right]$$

where each row of Y is the same, representing the imports to region j. We can consider only one region's consumption, and the result is $[a_{in}y_{nj}]$. Moreover, each element of $A \otimes Y$ stands for the same transport direction. So do the results of other production layers. For instance, in the second production layer, we look at $[a_{in}\sum_j^3 y_{nj}]$ in the same way we look at Y in the first layer. The calculation can be expressed in matrix form as follows:

$$PL_2 = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} * \begin{bmatrix} \sum_n^3 a_{1n}\sum_j^3 y_{nj} & \sum_n^3 a_{2n}\sum_j^3 y_{nj} & \sum_n^3 a_{3n}\sum_j^3 y_{nj} \\ \sum_n^3 a_{1n}\sum_j^3 y_{nj} & \sum_n^3 a_{2n}\sum_j^3 y_{nj} & \sum_n^3 a_{3n}\sum_j^3 y_{nj} \\ \sum_n^3 a_{1n}\sum_j^3 y_{nj} & \sum_n^3 a_{2n}\sum_j^3 y_{nj} & \sum_n^3 a_{3n}\sum_j^3 y_{nj} \end{bmatrix} \quad \text{(Equation 8)}$$

$$= \begin{bmatrix} a_{11}\sum_n^3 a_{1n}\sum_j^3 y_{nj} & a_{12}\sum_n^3 a_{2n}\sum_j^3 y_{nj} & a_{13}\sum_n^3 a_{3n}\sum_j^3 y_{nj} \\ a_{21}\sum_n^3 a_{1n}\sum_j^3 y_{nj} & a_{22}\sum_n^3 a_{2n}\sum_j^3 y_{nj} & a_{23}\sum_n^3 a_{3n}\sum_j^3 y_{nj} \\ a_{31}\sum_n^3 a_{1n}\sum_j^3 y_{nj} & a_{32}\sum_n^3 a_{2n}\sum_j^3 y_{nj} & a_{33}\sum_n^3 a_{3n}\sum_j^3 y_{nj} \end{bmatrix}$$

$$= \left[a_{qi}\sum_n^3 a_{in}\sum_j^3 y_{nj}\right]$$

Since the production layers expressed in SPA are infinite, it is unlikely that we can track all the cross-border trade. To reduce the error, we calculate up to 12 production layers (the 0^{th} production layer is the final consumption matrix) to ensure that more than 99% of all trade volumes $(I - A)^{-1}Y$ (in value) are included. The ratios of the sum of 12 production layers to all trade volumes from 1995 to 2015 are provided in Table 1.

The CFT of a certain region/country j can be calculated by combining global international exports in weight.

$$CFT_j = \sum_{k=0}^{11} PL_{kj} \Big/ \sum_j^M \sum_{k=0}^{11} PL_{kj} * Q * D_w \quad \text{(Equation 9)}$$

where PL_{kj} is the trade flows (in value) in the k^{th} production layer driven by the final consumption of region j; $\sum_j^M \sum_{k=0}^{11} PL_{kj}$ is the total trade flows (in value) driven by M regions (all the regions); Q is constructed on the basis of the CEPII-BACI database and represents total international trade flows (in weight, the same dimension as trade flows in value); and D_w is the weighted transport distances. We calculated D_w as

$$D_w = D_{sea} * \alpha_{sea} + D * (Z - \alpha_{sea}) \quad \text{(Equation 10)}$$

where Z represents the matrix with all elements set as 1; D_{sea} is the sea distance matrix obtained from the CERDI-sea distance database; D is the travel distance matrix obtained from the CEPII-GeoDist; and α_{sea} is the shipping shares matrix. Except for α_{sea}, we also determined α_{air}, α_{road}, and α_{rail} on the basis of existing modal shares and reported shipping and aviation freight turnover volumes.

The sub-turnover volumes by shipping, aviation, roads, and railways are calculated as follows:

$$CFT_{jt} = \sum_{k=0}^{11} PL_{kj} \Big/ \sum_j^M \sum_{k=0}^{11} PL_{kj} * Q * D_{sea} * \alpha_{sea} \ (t = shipping) \quad \text{(Equation 11)}$$

$$CFT_{jt} = \sum_{k=0}^{11} PL_{kj} \Big/ \sum_j^M \sum_{k=0}^{11} PL_{kj} * Q * D * \alpha_{air} \ (t = aviation) \quad \text{(Equation 12)}$$

$$CFT_{jt} = \sum_{k=0}^{11} PL_{kj} \Big/ \sum_j^M \sum_{k=0}^{11} PL_{kj} * Q * D * \alpha_{road} \ (t = roads) \quad \text{(Equation 13)}$$

$$CFT_{jt} = \sum_{k=0}^{11} PL_{kj} \Big/ \sum_j^M \sum_{k=0}^{11} PL_{kj} * Q * D * \alpha_{rail} \ (t = roads) \quad \text{(Equation 14)}$$

where the subscript t represents four transport modes (shipping, aviation, roads, and railways).

The corresponding CO_2 emissions are calculated as follows:

$$E_j = ef_t \sum_t CFT_{jt} \quad \text{(Equation 15)}$$

where ef_t is the CO_2 emission factor (g/t-km) of transport mode t.

Uncertainty analysis

The adopted macroeconomic approach based on MRIO provides a time-series overview of the worldwide freight turnover but also contains inherent drawbacks. First, the results do not support validation and regulation.[50] Second, our study is based on several assumptions due to the lack of reliable information.

- Assumption 1: the subregional modal shares of freight transport (exports and imports) are consistent with the continental data.

- Assumption 2: the transport distances along roads and railways and in aviation follow the great circle formula.[34]
- Assumption 3: the emission intensities under each transport mode remain the same throughout the years.
- Assumption 4: the different production layers share the same weight/value ratios.

Furthermore, our study is subject to methodology limitations and uncertainties in several factors.

First, elements of the Eora MRIO model, which was constructed under the assumption that national IO tables are mostly reliable, contain unavoidable errors. Since little information is given on the uncertainty in IO data, it is difficult to provide reliable standard deviations of the raw data used in the construction of Eora, in addition to the elements of the Eora model. According to a detailed comparison of four global MRIO models (https://worldmrio.com/comparison/)—namely, Eora, World Input-Output Database (WIOD), EXIOPOL, and Global Trade Analysis Project (GTAP)—the macroeconomic totals (GDP, imports, and exports) given by the various models differ to varying degrees both across regions and over time.

Second, owing to the limitations of SPA, the production layers embodied in the final consumption cannot be 100% traced.[66] We consider up to 12 production layers to decrease the error, and the trade flows in value are much closer to 100% (greater than 99% in each year, see Table 1).

Third, the same weight/value ratios are used to estimate sub-turnover volumes (Assumption 4). In fact, however, generally the upstream goods have a large mass and a small value. Thus, the estimations of upper production layers' weight are smaller.

Fourth, the limited available information on transport distances and modal shares may lead to skewed results (Assumptions 1 and 2). We acknowledge that the applied transport distances are divided between sea and other transport, both of which are not the actual hauling distances, especially smaller in the road and railway environments. In addition, there are no available detailed data on the modal shares of each pair of countries, and, therefore, we approximate the modal shares of the imports and exports of each continent.

Fifth, the chosen CO_2 emission factors (g/t-km) are based on previous studies and reports, but the real intensities change by modes and over time (Assumption 3). CO_2 emissions estimates have usually been determined according to the amount of fossil fuels burned during transportation (the top-down method) or abundant AIS data (the bottom-up method).[50] It is not practical to calculate these emissions directly and simply according to the freight turnover, although the emission intensity, as an important indicator, is listed after bottom-up or top-down estimates. However, we illustrate the importance of the immense differences in CFT over time and across regions, and, thus, we adopt the same emission factors in the different years and regions to estimate the potential environmental impacts entirely attributed to consumption drivers. Comparisons of the freight turnover and CO_2 emissions to available statistics are provided in Table S7. It is difficult to apply the Monte Carlo approach because little information on the SD of CO_2 emission factors (g/t-km) is available.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2022.09.007.

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AUTHOR CONTRIBUTIONS

Y.W. and J.L. designed research; Y.W. performed research and prepared the manuscript; and Y.W., J.L., and J.M. analyzed data. J.L. coordinated and supervised the project. All authors (Y.W., J.L., D.G., J.M., Z.L., S.X., H.Y., X.F., X.H., Q.Y., K.Y., Y.Z., J.M., X.W., and S.T.) contributed to manuscript revision and completion.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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