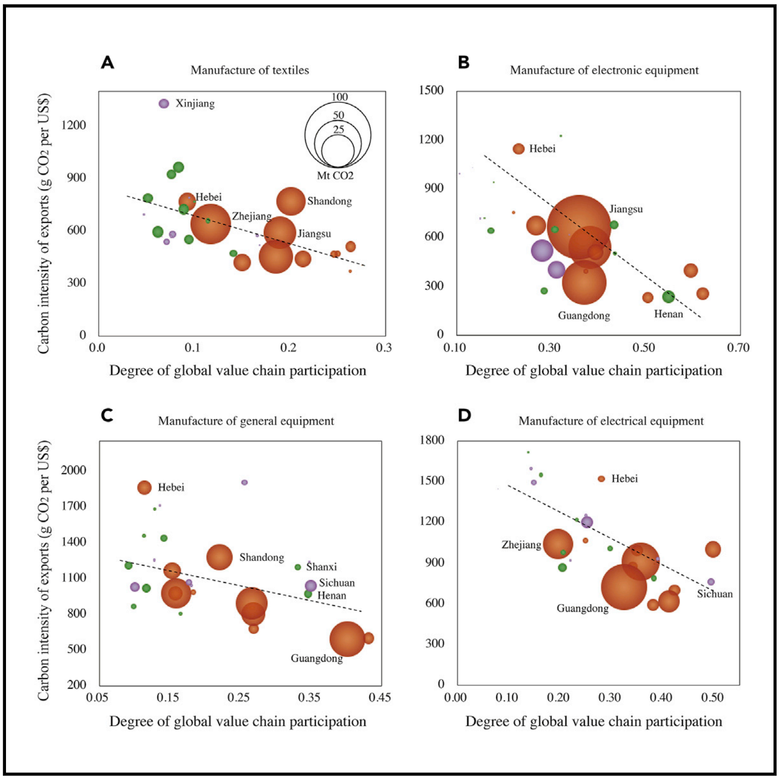
One Earth

Article

Production Globalization Makes China's Exports Cleaner

Graphical Abstract



Highlights

- We remap the carbon emissions embodied in China's exports
- China's processing exports are cleaner than ordinary exports
- Production globalization makes China's exports cleaner
- Deglobalization could threaten the international fight against climate change

Authors

Zengkai Zhang, Jing Meng, Heran Zheng, Kunfu Zhu, Huibin Du, Dabo Guan

Correspondence

zengkaizhang@tju.edu.cn (Z.Z.), zhukunfu@163.com (K.Z.), duhuibin@tju.edu.cn (H.D.), guandabo@tsinghua.edu.cn (D.G.)

In Brief

Globalization has enabled the international distribution of production. Production globalization could help developing countries avoid extra CO_2 emissions by allowing them to specialize in certain production activities. This study analyzes the impact of production globalization on the carbon intensity of exports in China while taking trade and spatial heterogeneity into account. We find that production globalization can make China's exports cleaner. We further point out that deglobalization could threaten the international fight against climate change.

Zhang et al., 2020, One Earth *2*, 468–478

https://doi.org/10.1016/j.oneear.2020.04.014

CellPress

CellPress OPEN ACCESS
Gold Standard for the Global Goals
3 tons of CO_2 offset
One Earth

Article

Production Globalization Makes China's Exports Cleaner

Zengkai Zhang,[1,2,7,8,*] Jing Meng,[3,7] Heran Zheng,[2,4,7] Kunfu Zhu,[5,*] Huibin Du,[1,*] and Dabo Guan[3,6,*]
[1]College of Management and Economics, Tianjin University, Tianjin 300072, China
[2]School of International Development, University of East Anglia, Norwich NR4 7TJ, UK
[3]Bartlett School of Construction and Project Management, University College London, London WC1E 7HB, UK
[4]Industrial Ecology Programme, Department of Energy and Process Technology, Norwegian University of Science and Technology, Trondheim 7010, Norway
[5]School of Economics, Renmin University of China, Beijing 100872, China
[6]Department of Earth System Science, Tsinghua University, Beijing 100084, China
[7]These authors contributed equally
[8]Lead Contact
*Correspondence: zengkaizhang@tju.edu.cn (Z.Z.), zhukunfu@163.com (K.Z.), duhuibin@tju.edu.cn (H.D.), guandabo@tsinghua.edu.cn (D.G.)
https://doi.org/10.1016/j.oneear.2020.04.014

SCIENCE FOR SOCIETY Globalization has enabled the international distribution of production. Although production globalization opens economic opportunities for developing countries, it also raises concerns about increasing emissions embodied in their exports. This study analyzes the impact of production globalization on the carbon intensity of exports in China while taking trade and spatial heterogeneity into account. We find that production globalization can make China's exports cleaner. If the degree of global value chain participation (which ranges from 0 to 1) increases by 0.1, the gross carbon intensity of China's exports will decrease by 11.7%. Our results suggest that developing countries could reduce the carbon intensity of their exports by becoming involved in global production networks if they specialize in relatively low-carbon production stages. However, the global economy has recently been in a deglobalization phase, which could make it more difficult to achieve the Paris Agreement target of 1.5°C.

SUMMARY

Production globalization, which is when firms expand their supply chains across national boundaries, creates an opportunity for developing countries to engage in international production networks via trade. Described as the world's factory, China specializes in assembly manufacturing mainly through processing exports. Firms use imported intermediate inputs for production and, after processing or assembly, reexport the finished products to international markets. Here, we show that the carbon efficiency of China's processing exports is greater than that of its ordinary exports. If the impact of trade heterogeneity is ignored, then the domestic emissions embodied in China's exports will be overestimated by 23.4%, and the foreign emissions embodied in China's exports will be underestimated by 29.3%. If the degree of global value chain participation, which ranges from 0 to 1, increases by 0.1, although foreign emissions embodied in China's exports would increase, the gross carbon intensity of China's exports will decrease by 11.7%.

INTRODUCTION

Production globalization enables developing countries to participate in global production networks via trade. However, the increasing emissions embodied in their exports[1–3] raises concerns about the trade-climate dilemma[4] in which international trade increases global emissions if emerging countries create more carbon emissions in the production of exports than those created in the production of the same product elsewhere. However, comparative advantage theory[5,6] implies that international trade will bring about environmental benefits even if a country is less carbon efficient in producing all its products. Globalization could help developing countries avoid extra CO_2 emissions by allowing them to specialize in the exports of relatively cleaner products than traditional carbon-intensive products.[7,8] This study attempts to analyze the trade-climate dilemma by focusing on the impact of production globalization on the carbon intensity of exports in developing countries.

This research question has important policy implications for analyzing the environmental efficiency of international production networks. Over the past few decades, the production system has become fragmented across national borders.[9] Developing countries specialize in certain production activities in which they have a comparative advantage and outsource other parts of the production process to foreign countries, which could be upstream suppliers or downstream assemblers. However, the recent world economy has been in a phase of deglobalization. The Economic Cycle Research Institute (ECRI) uses the difference between the growth rates of world trade and gross domestic product (GDP) to measure globalization and finds that structural deglobalization has been present (the difference between the growth rates of world trade and GDP is negative) since 2011.[10] With the rebuilding of international global networks, global emissions could increase significantly given that developing countries with higher carbon intensity have to rebuild their entire supply chains.

The literature has noted the large net carbon flows from developing countries to developed countries.[3,11] China, as the largest carbon emitter,[12,13] is also the largest net carbon exporter.[3] However, this phenomenon could be the result of a large trade deficit and cannot serve as direct evidence that emerging countries specialize in carbon-intensive production.[14] Described as the world's factory, China specializes in assembly manufacturing mainly through processing exports. Firms use imported intermediate inputs for production and, after processing or assembly, re-export the finished products to international markets.[15] For example, foreign intermediate inputs account for more than 95% of the iPhones exported from China.[16] Domestic intermediate inputs account for a greater share in the production of ordinary exports, and the literature has noted that processing exports generate relatively fewer emissions than ordinary exports do.[7,8,17–19] This study attempts to enrich the related literature from the following perspectives.

First, this study considers both domestic and foreign emissions embodied in exports to measure the environmental impacts of China's exports. In 2012, processing exports accounted for 42.11%[20] of China's gross exports, and the electronic equipment sector corresponds to the largest share. Previous related studies have mainly focused on domestic CO_2 emissions embodied in China's exports;[19] to the best of our knowledge, no study has distinguished the foreign emissions embodied in China's processing exports from those embodied in China's gross exports. This would leave open the question of the impact of China's production specialization on gross emissions embodied in China's exports, and this question has important policy implications for optimizing the global production network. In recent years, the increasing uncertainty of international trade has threatened the stability of the global carbon-flow network. As the world's largest carbon exporter, China plays an essential role in the global carbon-flow network. A change in China's exports influences not only domestic emissions but also the CO_2 emissions emitted by upstream input suppliers. For instance, China-US trade tensions in 2019 affected China's exports of manufacturing products, hence reducing the country's imports of upstream materials from foreign countries. This study extends beyond the national border and analyzes the spillover effect of China's trade decrease through global carbon-flow networks.

Second, trade heterogeneity[19] has a significant impact on the calculation of the CO_2 emissions embodied in China's exports, as well as spatial heterogeneity.[21] China shows a large provincial disparity in trade openness. Coastal provinces are closely involved in global supply chains and contributed to more than 80% of China's processing exports in 2012. Inland regions rely less on exports, but the exports that these regions do rely on are mainly in the form of ordinary exports. Previous studies noted the significant impact of spatial aggregation[21] and trade heterogeneity[19] on the calculation of the CO_2 emissions embodied in China's exports. This study attempts to combine these two lines of research and presents the first quantitative analysis of CO_2 emissions embodied in China's ordinary and processing exports at the provincial level. This approach could help in understanding the climate-trade dilemma in China and could assist policymakers in identifying targeted opportunities to address this dilemma.

Third, we construct an intercountry input-output database (ICIO) by using 2012 as the study year. This database contains 73 countries or regions based on the World Input-Output Database (WIOD)[22] and a provincial-level input-output table that captures processing exports. This dataset allows us to trace the sources and destinations of CO_2 emissions embodied in provincial exports. Methodologically, two main approaches exist for determining the environmental impacts of international trade via multi-regional input-output (MRIO) analysis. The first examines total bilateral trade between regions (the emissions embodied in bilateral trade [EEBT] approach), and the second considers trade to final consumption and endogenously determines trade to intermediate consumption (MRIO approach).[23] The MRIO approach has the advantage of reflecting international feedback effects. However, the traditional MRIO approach fails to capture the environmental impact of production globalization. To address this problem, this study adopts an extended MRIO approach that decomposes the Leontief inverse matrix. The extended MRIO approach not only considers inter-regional feedback effects but also allows us to trace the domestic and foreign CO_2 emissions embodied in provincial exports from both national and international perspectives. Finally, we simulate the correlation between the degree of global value chain (GVC) participation and the carbon intensity of exports. The domestic and foreign emissions embodied in China's exports are presented as follows.

RESULTS

Remapping the CO_2 Emissions Embodied in China's Exports

The results of this study show that the volume of CO_2 emissions embodied in China's exports in 2012 reached 2017.6 million tons. China emitted 1,701.4 million tons of CO_2 to produce its export products. Meanwhile, foreign countries emitted 316.2 million tons of CO_2 to produce intermediate inputs, which were transferred to China and used for producing the export products (see Tables S5–S7). The volume of foreign CO_2 emissions embodied in China's exports is comparable with the carbon emissions from fuel combustion in France in 2012.[24] In 2012, Guangdong Province emitted 206.2 million tons of CO_2 to

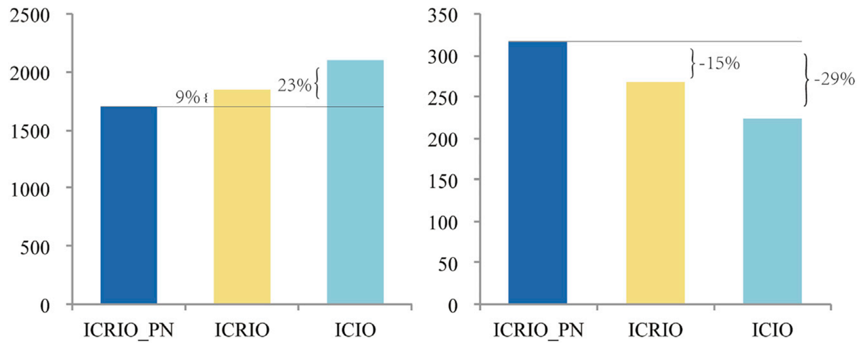


Figure 1. Comparison of the CO_2 Emissions Embodied in China's Exports (Million Tons)

Compared with the results based on the ICRIO_PN (intercountry input-output table that divides China into 30 provinces and captures provincial processing exports), the embodied emissions are overestimated or underestimated according to the ICRIO (intercountry input-output table that divides China into 30 provinces) and ICIO (intercountry input-output table from the WIOD). The degree of misestimation is also presented.

support China's exports and was the major source of the emissions embodied in China's exports, followed by Jiangsu (181.5 million tons) and Shandong (153.0 million tons). Korea's CO_2 emissions embodied in China's exports reached 22.7 million tons, followed by Chinese Taiwan (19.82 million tons) and the US (18.4 million tons). China's exports of industrial products correspond to the largest volume of embodied CO_2 emissions. For instance, the domestic and foreign CO_2 emissions embodied in the exports of electronic products reached 232.1 million tons and 93.6 million tons, respectively. This study further calculates the CO_2 emissions embodied in China's exports when trade heterogeneity and regional diversity are not taken into account. The estimation gap is presented in Figure 1.

Although previous studies noted that domestic CO_2 emissions from China's exports would be overestimated if trade heterogeneity were not taken into account,[19] no study has distinguished between the foreign emissions embodied in China's ordinary exports and those embodied in China's processing exports, leaving open the question of the degree to which misestimation is present. Figure 1 shows that if ordinary and processing exports are not distinguished for each province, then the domestic emissions embodied in China's exports will be overestimated by 8.6%, and the foreign emissions embodied in China's exports will be underestimated by 15.3%. If both regional diversity and trade heterogeneity are not taken into account, then the domestic emissions embodied in China's exports will be overestimated by 23.4%, and the foreign emissions embodied in China's exports will be underestimated by 29.3%. The overestimation of domestic emissions embodied in exports of Jiangsu and Guangdong reached 50.5 and 26.3 million tons, respectively (see Figures S1 and S2). In addition, other provinces' CO_2 emissions embodied in the exports of Jiangsu and Guangdong are overestimated by 19.1 and 9.0 million tons, respectively. Firms involved in processing exports mainly belong to industrial sectors. Domestic CO_2 emissions embodied in electronic equipment (sector C10) exports are overestimated by 80.0 million tons, followed by exports from the electrical machinery and equipment (sector C11; 71.4 million tons) and exports of metal products (sector C9; 66.8 million tons) (see Figures S3 and S4). Foreign CO_2 emissions embodied in electronic equipment (sector C10) exports are overestimated by 17.0 million tons, followed by exports of chemical products (sector C7; 71.4 million tons) and electrical machinery and equipment (sector C11; 66.8 million tons). The impact of trade heterogeneity on the calculation of carbon transfer from China to other regions is presented in Figure 2.

In 2012, the world's largest carbon flow through international trade was from China to the US, followed by the carbon transfer from China to the European Union (EU). The volume of carbon flows to the US and the EU reached 273.7 and 257.4 million tons, respectively. If trade heterogeneity is not taken into account, the volume of carbon transfer from China to the US and the EU will be overestimated by 27.9% and 20.0%, respectively. Developed countries are the major destinations of China's processing exports; therefore, the problem of the overestimation of carbon transfer from China to developed countries is serious. For instance, the carbon transfer from China to Japan will be overestimated by 28.6%. Moreover, the impact of trade heterogeneity on the calculation of the carbon transfer from China to developing countries, such as Russia, India, and Brazil, is not serious. The carbon transfer from China to Russia corresponds to the smallest degree of overestimation, which is only 5.6%. China's involvement in the global production network induces fewer emissions relative to the production taking place for ordinary exports. The traditional input-output model that adopts the homogeneity assumption would overestimate the carbon emissions embodied in China's processing exports. The impact of China's trade heterogeneity on the calculation of the carbon transfer related to China's exports is presented in Figure 3.

China plays an important role in the carbon flows that originate from neighboring countries or regions. For instance, the gross carbon flow from Korea to the US is 31.0 million tons, 16.26% (or 5.0 million tons) of which are emitted by Korea to support the production of China's exports, which are finally absorbed by the US. China is also actively participating in carbon flows that are sourced from Japan, Korea, and Australia. Korea's gross CO_2 emissions embodied in China's exports reached 22.7 million tons, followed by Chinese Taiwan (19.8 million tons) and the US (18.4 million tons). All these countries or regions are important suppliers of intermediate inputs, which China uses to produce export products. Korea, Chinese Taiwan, and Japan are the key suppliers of intermediate inputs to support China's processing exports. Therefore, the degree of the underestimation of carbon flows sourced from these three countries is much higher. The degree of the underestimation of Korea's emissions embodied in China's exports, which are finally absorbed by Japan, reaches as high as 55.9%. By ignoring trade heterogeneity, we will underestimate the impacts of China's exports on global carbon flows, especially for Korea, Japan, and Chinese Taiwan. As the economic links among different regions become increasingly closer, China's economic fluctuation could

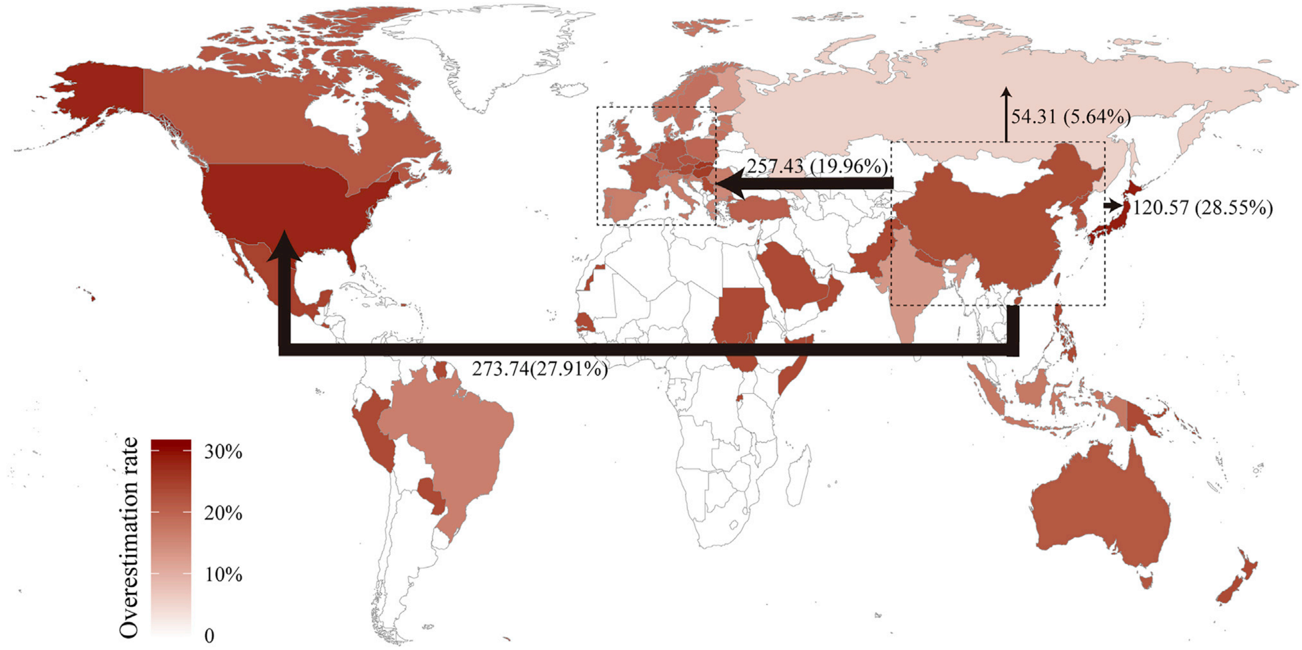


Figure 2. Overestimation of the Domestic CO_2 Emissions Embodied in China's Exports

The color of China represents the degree of overestimation of domestic emissions embodied in China's exports. The color of the other countries represents the degree of overestimation of carbon flows from China to these other countries. The arrows represent the carbon flows embodied in exports from China to other regions. The width of the arrows represents the volume of carbon flows (million tons). The arrow labels contain two parts: the volume of carbon flows and the degree of overestimation if trade heterogeneity is not taken into account. This study covers 27 EU countries and 13 other major countries (Supplemental Information section 2). The noncovered countries are referred to as the rest of the world (ROW).

spread along supply chains and threaten global production networks, at which point it becomes increasingly necessary to consider the spillover effect of a decrease in China's export on CO_2 emissions in foreign countries.

Comparison of CO_2 Emissions Embodied in Exports

In 2012, 79.3% of China's exported domestic CO_2 emissions were embodied in ordinary exports, whereas foreign CO_2 emissions embodied in processing exports accounted for 58.8% of China's exported foreign CO_2 emissions. Figure 4 shows the top five provinces and sectors for which ordinary or processing exports embodied the largest volume of domestic CO_2 emissions.

China shows a large provincial disparity in trade openness. Coastal provinces, relative to other provinces, are involved in the global production network in a more direct form[25] and contributed to more than 80% of China's processing exports in 2012. The top five provinces, which account for 66.5% of China's gross exported domestic emissions, are all located in the coastal region. Guangdong's ordinary exports correspond to the largest volume of exported domestic CO_2 emissions (265.6 Mt). The emissions embodied in ordinary exports are greater than those embodied in processing exports for the top five provinces. In addition, processing exports correspond to a lower ratio of exported domestic CO_2 emissions to export volume than ordinary exports do. For instance, the ratio of exported domestic emissions to Jiangsu's ordinary export volume reached 1.2 kg of CO_2 per unit of export, whereas the ratio of exported domestic emissions to Jiangsu's processing export volume was only 0.4 kg of CO_2 per unit of export. The ordinary exports of metal products, which have greater carbon intensity, correspond to the largest volume of exported domestic emissions (258.9 Mt). The ratio of exported domestic CO_2 emissions to export volume reached 2.2 kg of CO_2 per unit of ordinary export relative to the low ratio for processing exports (0.9 kg of CO_2 per unit of export). The processing exports of electronic products, which account for more than half of China's gross processing exports, correspond to the largest volume (150.0 Mt) of the domestic emissions embodied in processing exports. The ratio of domestic CO_2 emissions to the processing export volume of electronic products is only 0.4 kg of CO_2 per unit of export, which is even lower than that of the textile sector, which corresponds to the lowest level of domestic CO_2 emissions to ordinary export volume. Processing exports, which are the major form in which China is involved in the global production network, induces lower domestic emissions than ordinary exports do.

The top five provinces account for 78.5% of the gross foreign emissions embodied in China's exports. Guangdong's processing exports correspond to the largest volume (71.0 Mt) of exported foreign CO_2 emissions. Figure 5 shows that the ratio of exported foreign CO_2 emissions to processing export volume is greater than that of ordinary exports. The ratio of exported foreign emissions to Guangdong's ordinary export volume was 0.1 kg of CO_2 per unit of export, compared with the 0.3 kg of CO_2 per unit of export of Guangdong's processing exports. The processing exports of electronic equipment correspond to the largest volume (78.5 Mt) of exported foreign emissions. The ratio of exported foreign CO_2 emissions to export volume is

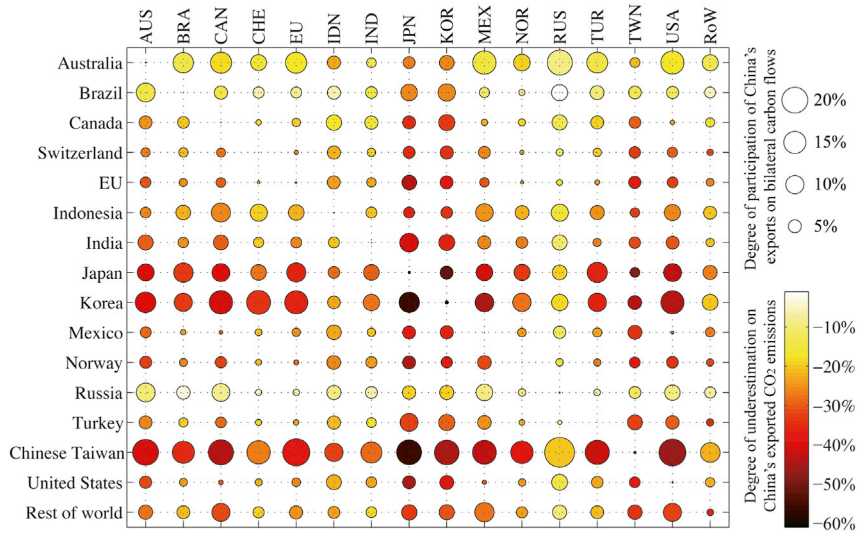


Figure 3. Underestimation of the Foreign CO_2 Emissions Embodied in China's Exports

The degree of the participation of China's exports in bilateral carbon flows is represented by the size of the circle, and the degree of the underestimation of a country's emissions embodied in China's exports, which are finally absorbed by a third country, is represented by the color.

0.2 kg of CO_2 per unit of export, compared with the low ratio of ordinary exports (0.1 kg of CO_2 per unit of export). If we measure the ratio of both the domestic and foreign emissions embodied in exports to export volume, the carbon intensity of ordinary exports is still greater than that of processing exports, although the volume of foreign emissions embodied in processing exports is greater than that embodied in ordinary exports. Some studies[14,26] have also measured production specialization by comparing the factor intensity of exports with the average factor intensity of total production. We find that the carbon intensity of processing exports is significantly lower than China's gross carbon intensity. In addition, we further calculate the domestic and foreign value added embodied in China's ordinary and processing exports. Processing exports are still cleaner than ordinary exports if the carbon intensity is measured according to the ratio of exported emissions to exported value added (Supplemental Information, section 7).[27,28] A clearer picture of global carbon-flow networks is the basis for determining trade-related climate regulations.[11,23,29] However, distinguishing between ordinary and processing exports for each region and sector is difficult. In practice, we suggest that policymakers focus on manufacturing exports in coastal regions where the processing export firms are concentrated.

GVC Participation and Exports' Carbon Intensity

Globalization implies the functional integration and coordination of internationally dispersed activities.[30] There are different forms of globalization,[31] such as social globalization, political globalization, economic globalization, and cultural globalization. This study focuses on production globalization, which means that firms expand their supply chains across national boundaries.[32] Different regions play different roles in global production networks with different degrees of GVC participation, measured by the ratio of foreign value added in a province's exports.[33,34] A region that is actively involved in production globalization has a greater degree of GVC participation. Similarly, the carbon footprint of a province's exports is made up of local emissions, other provinces' emissions, and foreign emissions. Other provinces' CO_2 emissions embodied in coastal provinces' exports account for a greater share of the CO_2 emissions embodied in the exports of coastal provinces (see Figure S6). Inland provinces indirectly engage in the global production network through supplying intermediate products to the coastal provinces to support the production of their exports. This section first illustrates the relationship between the degree of GVC participation and the ratio of exported domestic emissions to export volume (defined as carbon intensity). Production globalization mainly occurs in the manufacturing industry, and Figure 6 illustrates the results for four manufacturing sectors.

The ratio of exported domestic emissions to export volume decreases as the degree of GVC participation increases for the four major manufacturing sectors. A greater degree of GVC participation means that a region is more highly specialized in certain production stages. The negative correlation between exports' carbon intensity and the degree of GVC participation presented in Figure 6 shows that China specializes in relatively cleaner production activities than other countries. In global production networks, developed countries mainly outsource labor-intensive production to China,[35] which has abundant labor resources and lower labor costs. Although China emits more CO_2 in doing so than it would if it conducted these production stages elsewhere, the country reduces the emissions embodied in its exports by not using these resources to produce other more carbon-intensive exports. In recent years, firms involved in processing exports have moved from coastal provinces to inland provinces, such as Henan, Sichuan, and Shanxi; therefore, these inland provinces also correspond to a greater degree of GVC participation. However, the gross volume of exported CO_2 emissions is significantly smaller than that of coastal provinces. We further examine the correlation between the degree of GVC participation and the carbon intensity of China's exports for all manufacturing sectors. Table 1 shows that the ratio of exported domestic emissions to export volume will decrease by 21.3%[36] (according to Wooldridge's book, if the semi-elasticity is big enough, we have to adjust it by the equation $exp0.1\times\beta 1-1$ to show the change in the carbon intensity of exports if the degree of GVC participation increase by 0.1) if the degree of GVC participation, the range of which is 0–1, increases by 0.1. As China specializes in particular production activities, it relies more on imported inputs to produce exports. The foreign emissions embodied in China's exports could increase, which could partly offset the decrease in its exported domestic emissions. We further examine the correlations between globalization and the ratio of the foreign and gross emissions embodied in China's exports to export volume.

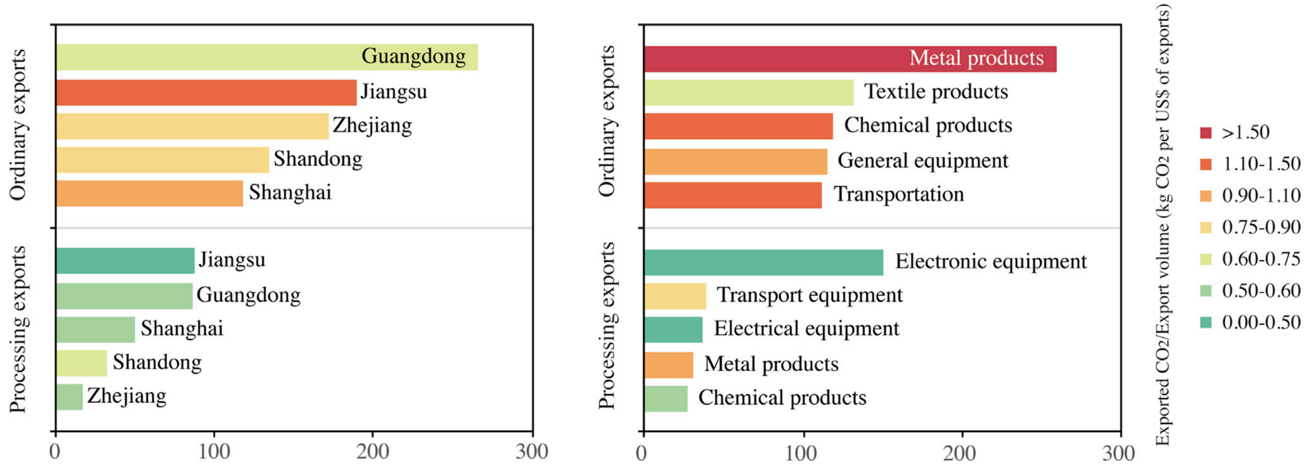


Figure 4. Top Five Exporting Provinces and Sectors of Embodied Domestic CO_2 Emissions (Mt CO_2)
The bar colors represent the exported CO_2 emissions per unit of export volume.

Taking the ratio of exported foreign emissions to export volume as the dependent variable, column 2 in Table 1 shows that the sign of the degree of GVC participation is significantly positive. The ratio of exported foreign emissions to export volume will increase by 20.4% if the degree of GVC participation increases by 0.1. The increase in the degree of GVC participation of China mainly promotes carbon emissions from some neighboring countries or regions. For instance, Korea, Chinese Taiwan, and the US are important suppliers of intermediate inputs, which China uses to produce exported products. The gross carbon flow from Korea to the US is 31.01 million tons, 16.26% (or 5.04 million tons) of which are emitted by Korea to support the production of China's exports, which are finally absorbed by the US. Column 3 considers both the domestic and foreign emissions embodied in China's exports. The sign of the degree of GVC participation is significantly negative. The gross carbon intensity of China's exports will decrease by 11.7% if the degree of GVC participation increases by 0.1. This means that the production globalization of China's exports reduces domestic emissions embodied in exports, although foreign emissions embodied in China's exports would increase. Production globalization means that China could replace its domestic intermediate inputs with imported intermediate inputs from developed countries to produce exports. Developed countries have lower carbon intensity than China; therefore, production globalization, characterized by an increase in intermediate products, can help in decreasing the carbon intensity of China's exports. We further check the relationship between the degree of GVC participation and the carbon intensity of exports at the sectoral and regional levels. The results show that sectoral and regional heterogeneity exist in the relationship. In addition, the results of the simulation using a quadratic equation show that the rate of decrease in the ratio of exported domestic emission to export volume accelerates with an increase in the degree of GVC participation (see Tables S8–S10).

DISCUSSION

With globalization, China has been actively involved in the international production framework and achieved rapid economic development. Given its coal-based energy mix, China emits more CO_2 for production than it would if the production were carried out elsewhere. However, China can generate CO_2 emissions savings by specializing in relatively cleaner production activities rather than exporting products with greater carbon intensity. By comparing ordinary and processing exports and simulating the correlation between globalization and the carbon intensity of exports, we show that production globalization can make China's exports cleaner. This study further discusses the future trends of global production networks and their impacts on carbon emissions.

First, there is a rising concern that the world economy is in a phase of deglobalization,[37] which will reshape global carbon-flow networks. In the short term, deglobalization will reduce international trade and the corresponding embodied carbon emissions. However, in the long run, deglobalization could threaten the international fight against climate change. Each country has to build more complete industrial systems to satisfy their final demand, although they have comparative disadvantages in some production stages. Rebuilding global supply chains will result in extra carbon emissions. This problem is more serious for developing countries, which have much greater carbon intensity and can no longer participate in global production networks through specializing in their relatively cleaner industries. In addition, deglobalization will hinder international cooperation, which is the basis for fighting climate change. The risk of free riding will increase. Policymakers should pay more attention to the potential impacts of deglobalization in fighting climate change.

Second, foreign enterprises are moving supply chains from China to other developing countries, such as Vietnam. These other developing countries are replacing China's position in global production networks, and the share of processing exports in China's gross exports has been decreasing in recent years. With continuously rising labor costs, China is trying to shift from exporting labor-intensive products to exporting technology-intensive products, which is characterized by higher value added and lower pollution. China has published annual catalogs of commodities prohibited from processing trade in recent years to restrict the processing trade of low-value-added and

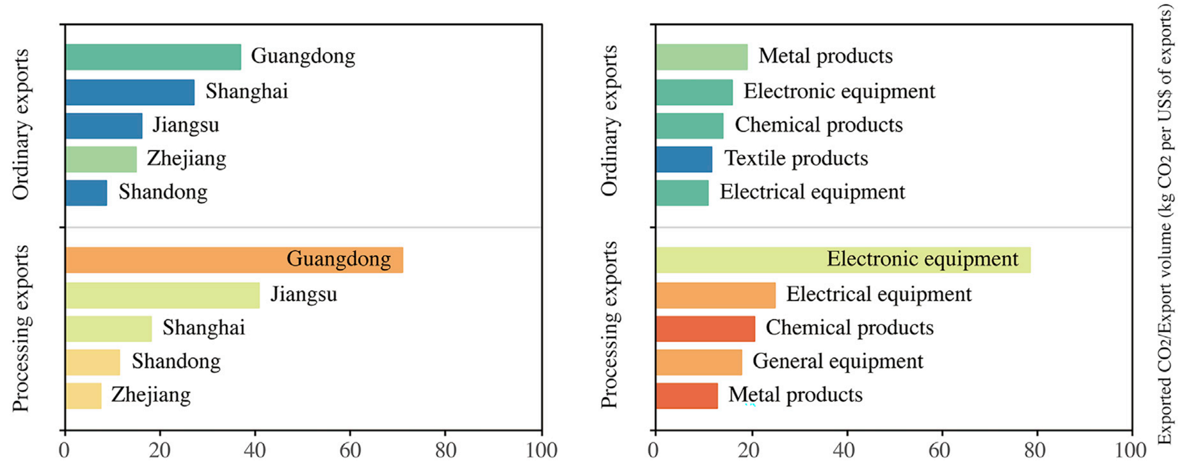


Figure 5. Top Five Exporting Provinces and Sectors of Embodied Foreign CO_2 Emissions (Mt CO_2)
The bar colors represent the exported CO_2 emissions per unit of the export volume.

high-pollution products. With the continuous optimization of the structure of exports, the carbon intensity of China's exports is expected to further decrease as China moves up the GVCs and gradually specializes in upstream activities. Meanwhile, China's experience can provide important guidance for other developing countries in solving their trade-climate dilemma. Developing countries should make full use of their comparative advantage to actively participate in global production networks, even if they have an absolute disadvantages relative to developed countries.

Production globalization not only creates new opportunities, such as easy access to capital,[38] rapid transfer of technology,[39] and efficient allocation of productive resources,[40] but also poses challenges to developing countries.[41] For instance, production globalization causes instability in the global production system and increases worker insecurity.[42] As an increasing number of regions are specialized in certain production activities where they have a comparative advantage,[9] the vulnerability of this supply chain is gradually becoming a major concern for policymakers. A country's economic fluctuation could spread along

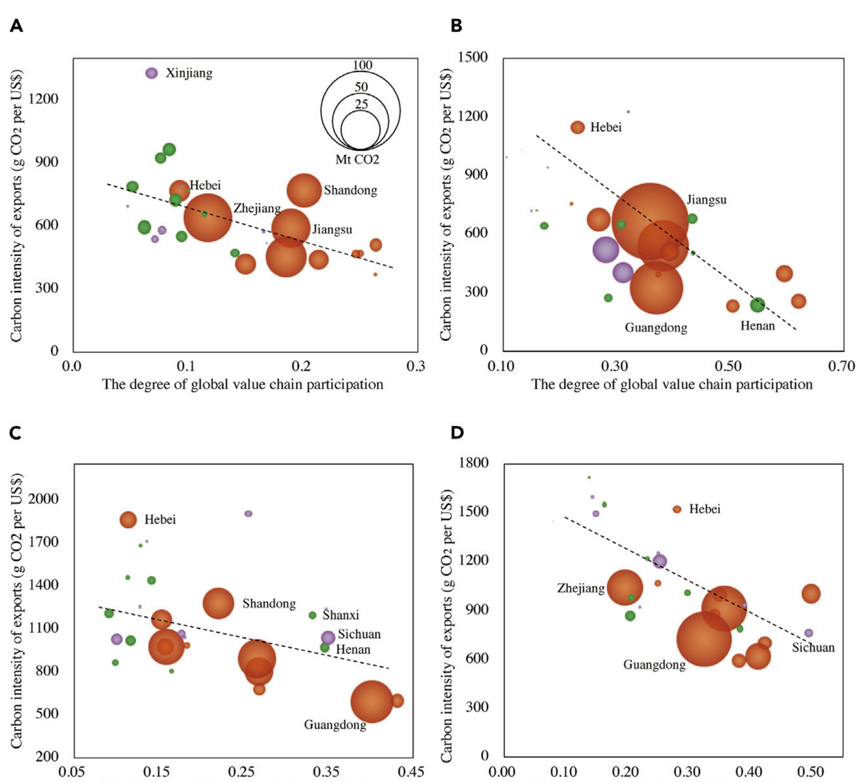


Figure 6. Negative Correlation between Globalization and the Carbon Intensity of Exports
Manufacture of (A) textiles, (B) electronic equipment, (C) general equipment, and (D) electrical equipment. The four panels share the same circle legend as presented in (A). The size of each circle denotes the province's gross exported embodied CO_2 emissions. The color of each circle represents whether a province is located in the eastern region (red), central region (green), or western region (purple).

Table 1. Correlation between Degree of GVC Participation and Carbon Intensity of Exports

	Ln(Carbon Intensity of Exports)		
Dependent Variable	Domestic Emissions	Foreign Emissions	Gross Emissions
Constant	6.90 (0.13)[a]	4.56 (0.13)[a]	6.88 (0.10)[a]
Degree of GVC participation	−2.39 (0.16)[a]	1.86 (0.16)[a]	−1.24 (0.12)[a]
Region fixed effects	yes	yes	yes
Sector fixed effects	yes	yes	yes
Observations	300	300	300
R^2	0.84	0.79	0.84

Standard errors are in parentheses.
[a]Significance at the 1% level.

supply chains and threaten global production networks, which is usually referred to as the spillover effect. A country's emissions are influenced by not only its exports but also the exports of other countries in the supply chain. As the world's largest carbon exporter,[2,3,11] China's potential export fluctuation could spread along supply chains and remap the global carbon-flow networks. In reviewing the impacts of the China-US trade tension, the International Monetary Fund noted that China's exports will decrease by 3.63%–5.54% if the US's tariff on China's exports increases by 25%.[43] This study adopts a scenario analysis of the potential impacts of a decrease in China's exports on the carbon emissions embodied in China's exports in 2012 (see Figure S7). We found that the spillover effect of China's trade decrease on the foreign emissions embodied in its exports is greater than the effect on its largest exporting province, Guangdong. Policymakers need to take into account the spillover effect to measure the environmental impacts of trade, especially for countries in the downstream position of global supply chains, such as China.

This study has limitations and several potential extensions that are worthy of pursuit. First, this study performed a static analysis of CO_2 emissions embodied in China's exports in 2012. Given that the provincial input-output table for 2017 is expected to be published in 2020, future studies are expected to update the database and analyze recent changes in embodied CO_2 emissions. Second, this study focuses on trade heterogeneity in China. However, processing exports could also account for a significant share in other developing countries, such as Mexico. Future studies can adopt this study's proposed method to discuss the impacts of production globalization on other developing countries if data are available. Third, this study only qualitatively discusses recent trends in production globalization and its potential impacts on global CO_2 emissions. Future studies are expected to provide quantitative calculations of the potential impacts of deglobalization.

EXPERIMENTAL PROCEDURES

Resource Availability

Lead Contact

For queries related to this article, please contact zengkaizhang@tju.edu.cn.

Materials Availability

Not applicable to this study.

Data and Code Availability

This study used different databases to construct the ICIO table that captures the processing exports of each sector in 30 provinces of China: (1) the (MRIO) table of China in 2012 constructed by the Development Research Center of the State Council,[44] (2) the national input-output table that captures processing exports, (3) trade data from China Customs Statistics, and (4) the 2012 ICIO table from the WIOD.[22] The construction process of the ICIO table is presented in the Supplemental Information. To combine data from different sources, we aggregated the sector level into 30 sectors (see Tables S1–S4). National CO_2 emissions data were obtained from the International Energy Agency.[45] China's provincial CO_2 emissions were obtained from China Emission Accounts & Datasets[46] (see Supplemental Information). Consistent with the literature,[18] this study split sectoral emissions into ordinary production and processing trade on the basis of the intermediate use of fuel resources and the corresponding carbon-emission coefficient. Zhang et al.[8] have noted that the emissions embodied in processing exports are mainly made up of indirect emissions, and the uncertainty in estimating the direct emissions coefficients has a limited impact on the calculation results. The data and code are available for academic use at http://dx.doi.org/10.17632/gyc2fp8hh4.2.

Calculation Methods

There are m regions, and each region has n sectors.

$$\mathbf{Y} = \begin{bmatrix} \mathbf{Y}_{11} & \mathbf{Y}_{12} & \cdots & \mathbf{Y}_{1m} \\ \mathbf{Y}_{21} & \mathbf{Y}_{22} & \cdots & \mathbf{Y}_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{Y}_{m1} & \mathbf{Y}_{m2} & \cdots & \mathbf{Y}_{mm} \end{bmatrix}$$

represents the flows of final outputs among different countries.

$$\mathbf{A} = \begin{bmatrix} \mathbf{A}_{11} & \mathbf{A}_{12} & \cdots & \mathbf{A}_{1m} \\ \mathbf{A}_{21} & \mathbf{A}_{22} & \cdots & \mathbf{A}_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{A}_{m1} & \mathbf{A}_{m2} & \cdots & \mathbf{A}_{mm} \end{bmatrix}$$

is the direct input-output coefficient matrix. According to the Leontief model,[47] the gross output $\mathbf{X}$ matrix is

$$\mathbf{X} = (\mathbf{I}-\mathbf{A})^{-1}\mathbf{Y}. \quad \text{(Equation 1)}$$

The Leontief inverse matrix is $\mathbf{B} = (\mathbf{I}-\mathbf{A})^{-1}$. $\mathbf{F}$ is the emissions coefficient matrix, and $\mathbf{V}$ is the value-added coefficient matrix. Then, the emissions induced by the final demand are

$$\mathbf{E} = \mathbf{FBY}. \quad \text{(Equation 2)}$$

According to the definition of $\mathbf{B}$, we have $(\mathbf{I}-\mathbf{A})\mathbf{B} = \mathbf{I}$. We define

$$\mathbf{A}_D = \begin{bmatrix} \mathbf{A}_{11} & 0 & \cdots & 0 \\ 0 & \mathbf{A}_{22} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \mathbf{A}_{mm} \end{bmatrix}$$

as the domestic inputs needed for each unit of main product outputs, and

$$\mathbf{A}_E = \begin{bmatrix} 0 & \mathbf{A}_{12} & \cdots & \mathbf{A}_{1m} \\ \mathbf{A}_{21} & 0 & \cdots & \mathbf{A}_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{A}_{m1} & \mathbf{A}_{m2} & \cdots & 0 \end{bmatrix}$$

represents the foreign inputs needed for each unit of main product outputs. By replacing $\mathbf{A}$ with $\mathbf{A}_D+\mathbf{A}_E$ in the equation $(\mathbf{I}-\mathbf{A})\mathbf{B} = \mathbf{I}$, we have

$$(\mathbf{I}-\mathbf{A}_D)\mathbf{B}-\mathbf{A}_E\mathbf{B} = \mathbf{I}. \quad \text{(Equation 3)}$$

We define the domestic Leontief inverse matrix as $\mathbf{L} = (\mathbf{I}-\mathbf{A}_D)^{-1}$. Multiplying both sides of Equation 3 by $\mathbf{L}$, we have

$$\mathbf{B}-\mathbf{L}\mathbf{A}_E\mathbf{B} = \mathbf{L}. \quad \text{(Equation 4)}$$

With rearrangement, we have $\mathbf{B} = \mathbf{L}+\mathbf{L}\mathbf{A}_E\mathbf{B}$. According to Equation 1, we obtain

$$\begin{aligned}\mathbf{E} &= \mathbf{F}(\mathbf{L}+\mathbf{L}\mathbf{A}_E\mathbf{B})\mathbf{Y}\\ &= \mathbf{F}(\mathbf{L}+\mathbf{L}\mathbf{A}_E\mathbf{L}+\mathbf{L}\mathbf{A}_E\mathbf{L}\mathbf{A}_E\mathbf{B})\mathbf{Y}\\ &= \mathbf{F}(\mathbf{L}+\mathbf{L}\mathbf{A}_E\mathbf{L}+\mathbf{L}\mathbf{A}_E\mathbf{L}\mathbf{A}_E\mathbf{L}+\mathbf{L}\mathbf{A}_E\mathbf{L}\mathbf{A}_E\mathbf{L}\mathbf{A}_E\mathbf{L}+\cdots)\mathbf{Y}\end{aligned} \quad \text{(Equation 5)}$$

We define $\mathbf{U} = \mathbf{A}_E\mathbf{L}$, foreign inputs driven by the production of one unit of output only through domestic industrial linkage. Then, we obtain

$$\mathbf{E} = \mathbf{FL}(\mathbf{I}+\mathbf{U}+\mathbf{U}^2+\cdots)\mathbf{Y}. \quad \text{(Equation 6)}$$

Equation 6 represents an important characteristic of production globalization, which is that intermediate products can cross national borders multiple times. $\mathbf{FLU}^k\mathbf{Y}$ represents carbon emissions embodied in supply chains, the intermediate inputs of which cross national borders k times.

$$\mathbf{Y}^{rs} = \begin{bmatrix} \mathbf{Y}_{11,rs} & \mathbf{Y}_{12,rs} & \cdots & \mathbf{Y}_{1m,rs}\\ \mathbf{Y}_{21,rs} & \mathbf{Y}_{22,rs} & \cdots & \mathbf{Y}_{2m,rs}\\ \vdots & \vdots & \ddots & \vdots\\ \mathbf{Y}_{m1,rs} & \mathbf{Y}_{m2,rs} & \cdots & \mathbf{Y}_{mm,rs}\end{bmatrix}$$

$$(\mathbf{Y}_{ij,rs} = \mathbf{Y}_{ij} \text{ if } r=i \text{ and } s=j;\ \text{otherwise, } \mathbf{Y}_{ij,rs}=0)$$

represents the bilateral trade in final products from country r to country s.

$$\mathbf{U}^{rs} = \begin{bmatrix} 0 & \mathbf{A}_{12,rs}\mathbf{L}_2 & \cdots & \mathbf{A}_{1m,rs}\mathbf{L}_m\\ \mathbf{A}_{21,rs}\mathbf{L}_1 & 0 & \cdots & \mathbf{A}_{2m,rs}\mathbf{L}_m\\ \vdots & \vdots & \ddots & \vdots\\ \mathbf{A}_{m1,rs}\mathbf{L}_1 & \mathbf{A}_{m2,rs}\mathbf{L}_2 & \cdots & 0\end{bmatrix}$$

$$(\mathbf{A}_{ij,rs} = \mathbf{A}_{ij} \text{ if } r=i \text{ and } s=j;\ \text{otherwise, } \mathbf{A}_{ij,rs}=0)$$

represents the bilateral trade linkage in intermediate products from country r to country s. According to Equation 6, carbon transfer that is not related to country r's exports to country s are

$$\mathbf{E}^{rs*} = \mathbf{FL}\left(\mathbf{I}+(\mathbf{U}-\mathbf{U}^{rs})+(\mathbf{U}-\mathbf{U}^{rs})^2+\cdots\right)(\mathbf{Y}-\mathbf{Y}^{rs}). \quad \text{(Equation 7)}$$

Then, the emissions embodied in country r's exports to country s are

$$\mathbf{E}^{rs} = \mathbf{E}-\mathbf{E}^{rs*}. \quad \text{(Equation 8)}$$

Although Equation 8 is intuitive, we cannot use it to calculate the carbon emissions embodied in country r's exports to country s because an infinite number of terms exist. By combing similar terms in Equation 8,

$$\begin{aligned}\mathbf{E}^{rs} &= \mathbf{FL}(\mathbf{I}+\mathbf{U}+\mathbf{U}^2+\cdots)\mathbf{Y}^{rs}+\mathbf{FL}(\mathbf{I}+\mathbf{U}+\mathbf{U}^2+\cdots)(\mathbf{Y}-\mathbf{Y}^{rs})\\ &\quad -\mathbf{FL}\left(\mathbf{I}+(\mathbf{U}-\mathbf{U}^{rs})+(\mathbf{U}-\mathbf{U}^{rs})^2+\cdots\right)(\mathbf{Y}-\mathbf{Y}^{rs})\\ &= \mathbf{FL}\Big\{\mathbf{I}+[\\ &\quad \times(\mathbf{U}-\mathbf{U}^{rs})+\mathbf{U}^{rs}]+[(\mathbf{U}-\mathbf{U}^{rs})+\mathbf{U}^{rs}]^2+\cdots\Big\}\mathbf{Y}^{rs}+\mathbf{FL}\Big\{\mathbf{U}^{rs}+[(\mathbf{U}-\mathbf{U}^{rs})+\mathbf{U}^{rs}]^2\\ &\quad -(\mathbf{U}-\mathbf{U}^{rs})^2+\cdots\Big\}(\mathbf{Y}-\mathbf{Y}^{rs})\\ &= \mathbf{FL}(\mathbf{M}+\mathbf{MU}^{rs}\mathbf{M}+\mathbf{MU}^{rs}\mathbf{MU}^{rs}\mathbf{M}+\cdots)\mathbf{Y}^{rs}+\mathbf{FL}(\mathbf{MU}^{rs}\mathbf{M}+\mathbf{MU}^{rs}\mathbf{MU}^{rs}\mathbf{M}+\cdots)\\ &\quad \times(\mathbf{Y}-\mathbf{Y}^{rs})\\ &= \mathbf{FL}(\mathbf{I}-\mathbf{MU}^{rs})^{-1}\mathbf{MY}^{rs}+\mathbf{FL}(\mathbf{I}-\mathbf{MU}^{rs})^{-1}\mathbf{MU}^{rs}\mathbf{M}(\mathbf{Y}-\mathbf{Y}^{rs})\\ &= \mathbf{FL}(\mathbf{I}-\mathbf{MU}^{rs})^{-1}[\mathbf{MU}^{rs}\mathbf{MY}+\mathbf{M}(\mathbf{I}-\mathbf{U}^{rs}\mathbf{M})\mathbf{Y}^{rs}],\end{aligned}$$

we obtain

$$\mathbf{E}^{rs} = \mathbf{FL}(\mathbf{I}-\mathbf{MU}^{rs})^{-1}[\mathbf{MU}^{rs}\mathbf{MY}+\mathbf{M}(\mathbf{I}-\mathbf{U}^{rs}\mathbf{M})\mathbf{Y}^{rs}], \quad \text{(Equation 9)}$$

where $\mathbf{M} = (\mathbf{I}-\mathbf{U}+\mathbf{U}^{rs})^{-1}$. On the basis of Equation 9, this study calculates carbon transfer related to region r's exports.

Country r's production of each sector could be divided into two parts: ordinary production (O) and production for processing exports (P). Then, the flow matrix of final outputs from country r to country s would be

$$\mathbf{Y}_{rs} = \begin{bmatrix}\mathbf{Y}_{rs}^P\\ \mathbf{Y}_{rs}^O\end{bmatrix}.$$

The direct input-output coefficient matrix from country r to country s would be

$$\mathbf{A}_{rs} = \begin{bmatrix}\mathbf{A}_{rs}^P\\ \mathbf{A}_{rs}^O\end{bmatrix}.$$

$$\mathbf{Y}^{rs\_P} = \begin{bmatrix} \mathbf{W}_{11}\mathbf{Y}_{11} & \mathbf{W}_{12}\mathbf{Y}_{12} & \cdots & \mathbf{W}_{1m}\mathbf{Y}_{1m}\\ \mathbf{W}_{21}\mathbf{Y}_{21} & \mathbf{W}_{22}\mathbf{Y}_{22} & \cdots & \mathbf{W}_{2m}\mathbf{Y}_{2m}\\ \vdots & \vdots & \ddots & \vdots\\ \mathbf{W}_{m1}\mathbf{Y}_{m1} & \mathbf{W}_{m2}\mathbf{Y}_{m2} & \cdots & \mathbf{W}_{mm}\mathbf{Y}_{mm}\end{bmatrix}$$

$$\left(\mathbf{W}_{ij} = \begin{bmatrix}\mathbf{I} & \mathbf{0}\\ \mathbf{0} & \mathbf{0}\end{bmatrix} \text{ if } r=i \text{ and } s=j;\ \text{otherwise, } \mathbf{W}_{ij} = \begin{bmatrix}\mathbf{0} & \mathbf{0}\\ \mathbf{0} & \mathbf{0}\end{bmatrix}\right)$$

represents the processing trade in final products from country r to country s.

$$\mathbf{Y}^{rs\_O} = \begin{bmatrix} \mathbf{W}_{11}\mathbf{Y}_{11} & \mathbf{W}_{12}\mathbf{Y}_{12} & \cdots & \mathbf{W}_{1m}\mathbf{Y}_{1m}\\ \mathbf{W}_{21}\mathbf{Y}_{21} & \mathbf{W}_{22}\mathbf{Y}_{22} & \cdots & \mathbf{W}_{2m}\mathbf{Y}_{2m}\\ \vdots & \vdots & \ddots & \vdots\\ \mathbf{W}_{m1}\mathbf{Y}_{m1} & \mathbf{W}_{m2}\mathbf{Y}_{m2} & \cdots & \mathbf{W}_{mm}\mathbf{Y}_{mm}\end{bmatrix}$$

$$\left(\mathbf{W}_{ij} = \begin{bmatrix}\mathbf{0} & \mathbf{0}\\ \mathbf{0} & \mathbf{I}\end{bmatrix} \text{ if } r=i \text{ and } s=j;\ \text{otherwise, } \mathbf{W}_{ij} = \begin{bmatrix}\mathbf{0} & \mathbf{0}\\ \mathbf{0} & \mathbf{0}\end{bmatrix}\right)$$

represents the processing trade in final products from country r to country s.

$$\mathbf{U}^{rs\_P} = \begin{bmatrix} 0 & \mathbf{W}_{12}\mathbf{A}_{12}\mathbf{L}_2 & \cdots & \mathbf{W}_{1m}\mathbf{A}_{1m}\mathbf{L}_m\\ \mathbf{W}_{21}\mathbf{A}_{21}\mathbf{L}_1 & 0 & \cdots & \mathbf{W}_{2m}\mathbf{A}_{2m}\mathbf{L}_m\\ \vdots & \vdots & \ddots & \vdots\\ \mathbf{W}_{m1}\mathbf{A}_{m1}\mathbf{L}_1 & \mathbf{W}_{m2}\mathbf{A}_{m2}\mathbf{L}_2 & \cdots & 0\end{bmatrix}$$

$$\left(\mathbf{W}_{ij} = \begin{bmatrix}\mathbf{I} & \mathbf{0}\\ \mathbf{0} & \mathbf{0}\end{bmatrix} \text{ if } r=i \text{ and } s=j;\ \text{otherwise, } \mathbf{W}_{ij} = \begin{bmatrix}\mathbf{0} & \mathbf{0}\\ \mathbf{0} & \mathbf{0}\end{bmatrix}\right)$$

represents processing trade linkages in intermediate products from country r to country s.

$$\mathbf{U}^{rs\_O} = \begin{bmatrix} 0 & \mathbf{W}_{12}\mathbf{A}_{12}\mathbf{L}_2 & \cdots & \mathbf{W}_{1m}\mathbf{A}_{1m}\mathbf{L}_m\\ \mathbf{W}_{21}\mathbf{A}_{21}\mathbf{L}_1 & 0 & \cdots & \mathbf{W}_{2m}\mathbf{A}_{2m}\mathbf{L}_m\\ \vdots & \vdots & \ddots & \vdots\\ \mathbf{W}_{m1}\mathbf{A}_{m1}\mathbf{L}_1 & \mathbf{W}_{m2}\mathbf{A}_{m2}\mathbf{L}_2 & \cdots & 0\end{bmatrix}$$

$$\left(\mathbf{W}_{ij} = \begin{bmatrix}\mathbf{0} & \mathbf{0}\\ \mathbf{0} & \mathbf{I}\end{bmatrix} \text{ if } r=i \text{ and } s=j;\ \text{otherwise, } \mathbf{W}_{ij} = \begin{bmatrix}\mathbf{0} & \mathbf{0}\\ \mathbf{0} & \mathbf{0}\end{bmatrix}\right)$$

represents ordinary trade linkage in intermediate products from country r to country s. By replacing $\mathbf{Y}^{rs}$ and $\mathbf{U}^{rs}$ in Equation 9 with $\mathbf{Y}^{rs\_P}$ and $\mathbf{U}^{rs\_P}$, we can calculate the carbon transfer related to region r's processing exports. By replacing $\mathbf{Y}^{rs}$ and $\mathbf{U}^{rs}$ in Equation 9 with $\mathbf{Y}^{rs\_O}$ and $\mathbf{U}^{rs\_O}$, we can calculate the carbon transfer related to region r's ordinary exports.

Replacing $\mathbf{F}$ in Equation 9 with $\mathbf{V}$, we obtain the value added $\mathbf{V}^{rs}$ embodied in country r's exports to country s.

$$\mathbf{V}^{rs} = \mathbf{VL}(\mathbf{I}-\mathbf{MU}^{rs})^{-1}[\mathbf{MU}^{rs}\mathbf{MY}+\mathbf{M}(\mathbf{I}-\mathbf{U}^{rs}\mathbf{M})\mathbf{Y}^{rs}] \quad \text{(Equation 10)}$$

The value added embodied in product exports from country r to country s in sector h is $\mathbf{V}^{rs,h}$. We separate $\mathbf{V}^{rs\_h}$ into two mn×m matrices $\mathbf{V}_D^{rs,h}$ and $\mathbf{V}_E^{rs,h}$, which satisfy $\mathbf{V}^{rs,h} = \mathbf{V}_D^{rs,h}+\mathbf{V}_E^{rs,h}$. $\mathbf{V}_D^{rs\_h}$ represents country r's value added embodied in the exports of sector h from country r to country s. $\mathbf{V}_E^{rs,h}$ represents the foreign value added embodied in the exports of sector h from country r to country s. We define $\mathbf{p}$ as a 1×mn sum vector and $\mathbf{q}$ as a m×1 sum vector. Country r's degree of GVC participation in sector h is measured by the ratio of foreign value added to a province's exports.[33,34]

$$G^{r-h} = \frac{\sum_s \mathbf{p}\mathbf{V}_E^{rs,h}\mathbf{q}}{\sum_s \mathbf{p}\mathbf{V}^{rs,h}\mathbf{q}} \quad \text{(Equation 11)}$$

Similarly, the volume of CO_2 emissions embodied in exports of sector h in country r is $\sum_s \mathbf{p}\mathbf{E}^{rs,h}\mathbf{wq}$. We divide the volume of exports to obtain the carbon intensity of exports C^{r-h}. This study employs a cross-section regression analysis to estimate the correlation between the degree of GVC participation and the carbon intensity of exports. The correlation regression equation is as follows:

$$\ln C^{r-h} = \beta_0 + \beta_1 G^{r-h} + \beta_s + \beta_r + \mu_{sr}, \quad \text{(Equation 12)}$$

where β_0 is the consistent effect, β_1 is the semi-elasticity of the carbon intensity of exports with respect to globalization, β_s is the sector fixed effect, β_r is the region fixed effect, and μ_{sr} is the idiosyncratic error term.

SUPPLEMENTAL INFORMATION

Supplemental Information can be found online at https://doi.org/10.1016/j.oneear.2020.04.014.

ACKNOWLEDGMENTS

A previous version of this paper was presented at the 27th International Input-Output Association Conference. We are grateful for comments and suggestions from Dr. Anne Owen and other conference participants. The authors gratefully acknowledge the financial support from the National Key R&D Program of China (2018YFC0213600), National Natural Science Foundation of China (71974141, 71603179, 71834004, 71733002, 71673198, 41921005, and 91846301), UK Natural Environment Research Council (NE/N00714X/1 and NE/P019900/1), and British Academy (NAFR2180103). We also would like to thank the anonymous referees.

AUTHOR CONTRIBUTIONS

D.G., H.D., and Z.Z. designed the research. Z.Z. and K.Z. determined the calculation method. Z.Z. J.M., and H.Z. carried out the calculations and analysis. Z.Z. wrote the manuscript, and all authors contributed to this manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.

Received: November 5, 2019
Revised: March 15, 2020
Accepted: April 28, 2020
Published: May 22, 2020

REFERENCES

1. Meng, J., Mi, Z., Guan, D., Li, J., Tao, S., Li, Y., Feng, K., Liu, J., Liu, Z., Wang, X., et al. (2018). The rise of South-South trade and its effect on global CO_2 emissions. Nat. Commun. *9*, 1–7.
2. Davis, S.J., and Caldeira, K. (2010). Consumption-based accounting of CO_2 emissions. Proc. Natl. Acad. Sci. USA *107*, 5687–5692.
3. Peters, G.P., Minx, J.C., Weber, C.L., and Edenhofer, O. (2011). Growth in emission transfers via international trade from 1990 to 2008. Proc. Natl. Acad. Sci. USA *108*, 8903–8908.
4. Liu, Z., Davis, S.J., Feng, K., Hubacek, K., Liang, S., Anadon, L.D., Chen, B., Liu, J., Yan, J., and Guan, D. (2015). Targeted opportunities to address the climate–trade dilemma in China. Nat. Clim. Chang. *145*, 143–145.
5. Costinot, A., and Donaldson, D. (2012). Ricardo's theory of comparative advantage : old idea, new test. Am. Econ. Rev. *102*, 453–458.
6. Pethig, R. (1976). Pollution, welfare, and environmental policy in the theory of comparative advantage. J. Environ. Econ. Manage. *2*, 160–169.
7. Su, B., Ang, B.W., and Low, M. (2013). Input-output analysis of CO_2 emissions embodied in trade and the driving forces: processing and normal exports. Ecol. Econ. *88*, 119–125.
8. Zhang, Z., Duan, Y., and Zhang, W. (2019). Economic gains and environmental costs from China's exports: regional inequality and trade heterogeneity. Ecol. Econ. *164*, 106340.
9. Timmer, M., Erumban, A., Los, B., Stehrer, R., and de Vries, G. (2014). Slicing up global value chains. J. Econ. Perspect. *28*, 99–118.
10. Economic Cycle Research Institute (2019). De-globalization diagnosis predated trade war. http://m.businesscycle.com/ecri-news-events/news-details/economic-cycle-research-ecri-lakshman-achuthan-business-cycle-ecri-de-globalization-diagnosis-predated-trade-war.
11. Davis, S.J., Peters, G.P., and Caldeira, K. (2011). The supply chain of CO_2 emissions. Proc. Natl. Acad. Sci. U S A *108*, 18554–18559.
12. Guan, D., Liu, Z., Geng, Y., Lindner, S., and Hubacek, K. (2012). The gigatonne gap in China's carbon dioxide inventories. Nat. Clim. Chang. *2*, 1–4.
13. Guan, D., Meng, J., Reiner, D.M., Zhang, N., Shan, Y., Mi, Z., Shao, S., Liu, Z., Zhang, Q., and Davis, S.J. (2018). Structural decline in China's CO_2 emissions through transitions in industry and energy systems. Nat. Geosci. *11*, 551–555.
14. Jakob, M., and Marschinski, R. (2012). Interpreting trade-related CO_2 emission transfers. Nat. Clim. Chang. *3*, 19–23.
15. Yang, C., Dietzenbacher, E., Pei, J., Chen, X., Zhu, K., and Tang, Z. (2015). Processing trade biases the measurement of vertical specialization in China. Econ. Syst. Res. *27*, 60–76.
16. Xing, Y., and Detert, N. (2010). How the iPhone widens the United States trade deficit with the People's Republic of China. ADBI Working Paper 257 (Asian Development Bank Institute).
17. Jiang, X., Guan, D., Zhang, J., Zhu, K., and Green, C. (2015). Firm ownership, China's export related emissions, and the responsibility issue. Energy Econ. *51*, 466–474.
18. Xia, Y., Fan, Y., and Yang, C. (2015). Assessing the impact of foreign content in China's exports on the carbon outsourcing hypothesis. Appl. Energy *150*, 296–307.
19. Dietzenbacher, E., Pei, J., and Yang, C. (2012). Trade, production fragmentation, and China's carbon dioxide emissions. J. Environ. Econ. Manage. *64*, 88–101.
20. National Bureau of Statistics (2013). National Economic and Social Development Statistics Bullet in 2012 (China Statistics Press).
21. Su, B., and Ang, B.W. (2010). Input-output analysis of CO_2 emissions embodied in trade: the effects of spatial aggregation. Ecol. Econ. *70*, 10–18.
22. Timmer, M.P., Dietzenbacher, E., Los, B., Stehrer, R., and de Vries, G.J. (2015). An illustrated user guide to the World Input-Output Database: the case of global automotive production. Rev. Int. Econ. *23*, 575–605.
23. Peters, G.P. (2008). From production-based to consumption-based national emission inventories. Ecol. Econ. *65*, 13–23.
24. International Energy Agency (2018). CO_2 emissions from fuel combustion: 2018 highlights.
25. Feng, K., Davis, S.J., Sun, L., Li, X., Guan, D., Liu, W., Liu, Z., and Hubacek, K. (2013). Outsourcing CO_2 within China. Proc. Natl. Acad. Sci. U S A *110*, 11654–11659.
26. Learner, E.E. (1980). The Leontief paradox reconsidered. J. Polit. Econ. *88*, 495–503.
27. Zhang, W., Liu, Y., Feng, K., Hubacek, K., Wang, J., Liu, M., Zhang, W., Liu, Y., Feng, K., Hubacek, K., et al. (2018). Revealing environmental inequality hidden in China's inter-regional trade. Environ. Sci. Technol. *52*, 7171–7181.
28. Zhang, W., Wang, F., Hubacek, K., Liu, Y., Wang, J., Feng, K., Jiang, L., Jiang, H., Zhang, B., and Bi, J. (2018). Unequal exchange of air pollution and economic benefits embodied in China's exports. Environ. Sci. Technol. *52*, 3888–3898.

29. Zhang, Z., Zhang, Z., and Zhu, K. (2019). Allocating carbon responsibility: the role of spatial production fragmentation. Energy Econ. https://doi.org/10.1016/j.eneco.2019.104491.

30. Dicken, P. (2011). Global Shift: Mapping the Changing Contours of the World Economy (The Guilford Press).

31. Goryakin, Y., Lobstein, T., James, W.P.T., and Suhrcke, M. (2015). The impact of economic, political and social globalization on overweight and obesity in the 56 low and middle income countries. Soc. Sci. Med. *133*, 67–76.

32. Koopman, R., Wang, Z., and Wei, S.-J. (2014). Tracing value added and double counting in gross exports. Am. Econ. Rev. *104*, 0–41.

33. Yi, K.-M. (2003). Can vertical specialization explain the growth of world trade? J. Polit. Econ. *111*, 52–102.

34. Hummels, D., Ishii, J., and Kei-Mu, Y. (2001). The nature and growth of vertical Specialization in world trade. J. Int. Econ. *54*, 75–96.

35. Wang, Z., Wei, S.-J., Yu, X., and Zhu, K. (2016). Characterizing global value chains: production length and upstreamness. NBER Working Paper No. 23261 (National Bureau of Economic Research). http://www.nber.org/papers/w23261.

36. Wooldridge, J.M. (2015). Introductory Econometrics: A Modern Approach (Nelson Education).

37. James, H. (2018). Deglobalization : the rise of disembedded unilateralism. Annu. Rev. Financ. Econ. *10*, 219–237.

38. Obstfeld, M., and Taylor, A.M. (2003). Globalization and capital markets. In Globalization in Historical Perspective, M.D. Bordo, A.M. Taylor, and J.G. Williamson, eds. (University of Chicago Press), pp. 121–188.

39. Şener, F., and Zhao, L. (2009). Globalization, R&D and the iPod cycle. J. Int. Econ. *77*, 101–108.

40. Mcmillan, M.S., and Rodrik, D. (2011). Globalization, structural change and productivity growth. NBER Working Paper No. 17143 (National Bureau of Economic Research). https://www.nber.org/papers/w17143.

41. Fischer, S. (2003). Globalization and its challenges. Am. Econ. Rev. *93*, 1–30.

42. Scheve, K., and Slaughter, M.J. (2004). Economic insecurity and the globalization of production. Am. J. Pol. Sci. *48*, 662–674.

43. Eugster, J., Jaumotte, F., MacDonald, M., and Piazza, R. (2019). Chapter 4: the drivers of bilateral trade and the spillovers from tariffs. In World Economic Outlook: Growth Slowdown, Precarious Recovery (International Monetary Fund). https://www.imf.org/en/Publications/WEO/Issues/2019/03/28/world-economic-outlook-april-2019.

44. Pan, C., Peters, G.P., Andrew, R.M., Korsbakken, J.I., Li, S., Zhou, P., and Zhou, D. (2018). Structural changes in provincial emission transfers within China. Environ. Sci. Technol. *52*, 12958–12967.

45. International Energy Agency (2014). 2012 CO_2 emissions overview. https://www.iea.org/subscribe-to-data-services/co2-emissions-statistics.

46. Shan, Y., Guan, D., Zheng, H., Ou, J., Li, Y., Meng, J., Mi, Z., Liu, Z., and Zhang, Q. (2018). China CO_2 emission accounts 1997-2015. Sci. Data *5*, 1–14.

47. Leontief, W.W. (1936). Quantitative input-output relations in the economic system of the United States. Rev. Econ. Stat. *18*, 105–125.