Reassessing the embodied carbon emissions in China’s foreign trade: a new perspective from the export routes based on the global value chain

Boya Zhang1 · Yadong Ning1 · Shukuan Bai1

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Abstract
A new route perspective measure based on the global value chain (GVC) distinguishes the embodied emission transfer destinations while concurrently considering the transfer process and GVC embedding position. This study applies this measure to reassess the characteristics of China’s foreign trade embodied emissions and their impacts on global emissions. The results show that: (1) China’s domestic embodied emission exports are mainly concentrated in manufacturing and dominated by final goods exports and simple GVC routes. China primarily imports foreign emissions via simple GVC routes. (2) The embodied emission intensity of China’s exports is much higher than that of its imports, and China’s expansion in imports indirectly promoted global emission reduction. (3) China’s foreign trade increases global emissions with a waning trend, while GVC-related trade reduces global emissions. Additionally, it is feasible to reduce global emissions by adjusting China’s bilateral trade structures with different countries. We conclude that China’s GVC-related trade has increased, but exports through complex GVC tend to be the resource-input type. We emphasize that China needs to actively participate in globalization and upgrade its GVC to step off the low-end locking predicament in global production and cope with the multiple pressures of global and domestic emission reduction and stable development.

Keywords Embodied carbon emission · Global value chain · International trade · Emission transfer route · China

Introduction
Climate change is closely related to human survival and social development, and combating climate change is an important global issue. Massive and growing carbon emissions resulting from global economic growth and industrialization are the leading causes of climate change. The environment is a non-exclusive public good; thus, combating climate change requires all countries to participate in action (Liu and Zhao 2021), making carbon emissions an important international political and economic issue in recent decades. Some developed countries tend to import carbon-intensive products from countries with weak environmental regulations to reduce their domestic emissions (Antweiler et al. 2001; Copeland and Taylor 1994). International trade has become a reallocation mechanism for pollution emissions (Duan et al. 2021). When developing countries relatively fall behind in terms of productivity in carbon-intensive industries, global emissions may increase due to international trade, resulting in carbon leakage. Many studies on international trade and embodied emissions have demonstrated that emissions embodied in international trade (EEIT) can lead to carbon leakage (Lin and Sun 2010; Mongelli et al. 2006). Better management measures for EEIT are needed to ensure global emission reduction and combat climate change. The accurate measurement of EEIT is a fundamental prerequisite.
However, with the rapid growth of globalization and the deepening of global labor division, intermediate trade gradually occupies a dominant position in international trade. In particular, some intermediate products may cross borders back and forth, thus making it difficult to calculate the relevant EEIT. Therefore, it is necessary to pay attention to both direct trade partners and all third parties involved in the entire trade process. Comprehensive identification of the initial sources and final absorptions helps depict EEIT transfer routes. Such analyses are more conducive to clarifying the transfer process of emissions and play a vital role in formulating effective emission reduction policies and management programs and reducing carbon leakage.

Moreover, facing the irreversible trends of globalization, the growth of international trade is inevitable, and all countries and regions are committed to enhancing their position in the global production chain. Carbon emissions are closely related to production and value chains. In the context of global emission reduction, the improvement of the value chain should consider both the economic benefits and the impact on global emissions. A detailed analysis of EEIT transfer routes and the impacts of foreign trade on global emissions is conducive to identifying the direction of value chain upgrades for emission reduction.

However, existing research on EEIT focuses solely on direct trade parties and ignores other participants in the whole trade process. For example, some have analyzed the EEIT at a national level, such as Brazil (Schaeffer and De Sá 1996), Australia (Lenzen 1998), Spain (Sánchez-Chóliz and Duarte 2004), Italy (Mongelli et al. 2006), and the UK (Wiedmann et al. 2010). Some studies have been conducted at the international level (Ahmad and Wyckoff 2003; Chen and Chen 2011; Ding et al. 2018; Peters and Hertwich 2008; Tian et al. 2015). These studies regarded the total emissions embodied in trade between two direct trade partners as the transfer of embodied emissions. However, they did not consider the complex sources and whereabouts of the trade process and ignored the possible problems of double-counting in the calculation, which may lead to misunderstandings of EEIT. Especially for China, which has large amounts of processing trade, this kind of problem may be more pronounced. Given the characteristics of China as a major country in the global economy, trading, and carbon emissions, the issue of China’s EEIT has attracted widespread attention. In addition, among existing studies on EEIT, research on China’s EEIT accounts for a large proportion, covering various types and methods of research on embodied emissions.

China is the largest carbon emitter and foreign trading country. According to the WTO data, China’s foreign trade value reached 5.36 trillion USD in 2019 (WTO 2021), accounting for 10.72% of the total global trade value. The IEA data shows that China’s carbon emissions reached 9919.1 Mt (IEA 2021), accounting for 29.50% of global emissions. China’s emissions have been the focus of global emission reduction. From the perspective of emission reduction, internally, the Chinese government has put forward targets for carbon peaking and carbon neutrality; carbon emission reduction is an essential direction for China’s future development. Externally, China is facing tremendous pressure and a problematic situation of global emission reduction. Therefore, the measurement and assessment of China’s EEIT are essential for the emission reduction of both China and the world.

In recent decades, especially after China acceded to the WTO, studying China’s EEIT has become a hot topic in related fields. Many studies have been conducted on China’s EEIT (Dietzenbacher et al. 2012; Lin and Sun 2010; Pan et al. 2008; Shui and Harriss 2006; Su and Ang 2014; Su and Thomson 2016; Weber et al. 2008). However, owing to the limitations of technology and methods, there are more or fewer deficiencies in early related studies. In addition, with the rapid development of international trade and the continuous improvement of the international division of labor, the global value chain (GVC) trade pattern characterized by the repeated cross borders of intermediate goods has come into being. The calculation of EEIT based on gross value statistics in previous studies could no longer accurately reflect the actual situation of EEIT transfer. With the advent of trade-in-value-added accounting and the development of GVC theory, it is possible to completely decompose the value-added in international trade according to sources, destinations, and transfer routes, which also provides new measures for EEIT.

The calculation of GVC started with the study by Hummels et al. They first defined a narrow concept of vertical specialization and proposed a quantitative index of systematic measurement, which could measure GVC (Hummels et al. 2001). Since then, the methodology has been continuously developed based on aspects of the accounting framework (Koopman et al. 2008, 2010, 2014; Los et al. 2016; Los and Timmer 2018; Wang et al. 2014), as well as measurement indicators (Daudin et al. 2011; Dietzenbacher et al. 2005; Johnson and Noguera 2018; Stehrer 2012; Wang et al. 2017). Wang et al. compared the trade-in value-added accounting method with the gross value accounting system from gross exports and decomposed total exports into 16 value-added components and double-counting items, thus realizing the complete decomposition of gross exports (Wang et al. 2014). Today, the decomposition framework for GVC accounting has been completed. The gross exports are further decomposed into 17 components to consider the final destination of the exports better, and this application calculates carbon transfer more accurately (Fei et al. 2020; Zhang et al. 2021; Bai et al. 2022).
In recent years, some studies have traced the EEIT by combining the multi-region input–output (MIRIO) model and value-added accounting. Zhao et al. investigated China’s EEIT based on the work of Hummels et al. They pointed out that the rise in China’s EEIT was mainly driven by the increase in re-exported emissions in China’s imported intermediate inputs (Hummels et al. 2001; Zhao et al. 2014). Xu et al. recalculated China’s EEIT based on the model proposed by Koopman et al. and found that traditional trade statistics overestimated China’s emissions in trade (Koopman et al. 2014; Xu et al. 2017). Meng et al. proposed a unified framework to trace a country’s embodied emissions in GVC (Meng et al. 2018). However, they did not conduct a detailed analysis of the EEIT. Dai et al. followed Los and Timmer’s framework and calculated the embodied emissions in China-US trade (Dai et al. 2021; Los and Timmer 2018). Xiong and Wu also analyzed the economic benefits and environmental costs of China-US trade following Wang’s framework (Xiong and Wu 2021). Both studies highlight the imbalance in bilateral trade between China and the USA. Li et al. weighed China’s EEIT and value-added and pointed out that GVC-related emissions exacerbate China’s economic-environmental imbalance (Li et al. 2022).

Some studies have also examined the impact of the GVC location on carbon emissions. Zhang et al. adopted a regression analysis of export embodied emissions and the GVC participation index (calculated as the foreign component in gross exports) and concluded that production globalization makes China’s exports cleaner (Zhang et al. 2020). Liu and Zhao adopted the GVC participation (measured by production length) to represent the degree of GVC embedment and conducted a regression analysis on GVC participation and emission intensity (Liu and Zhao 2021). Chen et al. simultaneously estimated these two indicators’ impacts on China’s EEIT (Chen et al. 2022). These two indicators are the leading indicators for measuring the degree of GVC embedment. Nevertheless, the former focuses on foreign inputs in export production and ignores the impact of the embedding position. For example, when a country is engaged in the final assembly stage of the global production of machinery and equipment, its participation in GVC is high in terms of the foreign component of the exports, even though the country is downstream in the production chain. The GVC participation index considers the entire production process (including domestic and foreign stages). Wang et al. claimed that the greater the number of downstream production stages, the more upstream side of the production chain the input is (Wang et al. 2017). To focus on the foreign production stage after the export of products, that is, considering the exporter’s position in the GVC of the subsequent production chain, this study puts forward a new perspective on export routes to analyze embodied emissions exports.

Summarizing the existing literature, the theories and methods of EEIT accounting have made significant progress in recent decades. However, with the development of the GVC theory and technology and the enrichment of databases related to global trade and carbon emissions, several considerations can be expanded in the following aspects. First, most previous studies adopted measures based on gross-value accounting and only focused on direct trade partners. Trade-in value-added accounting and the GVC-based measure can avoid the double-counting problem in the previous method and consider participants in the whole trade process. Second, previous studies mainly concentrated on the value of gross emissions in exports and imports and ignored the analysis of the process and transfer routes. The transfer routes of export embodied emissions are closely related to the location in the GVC, and the route-based study on EEIT reflects the impact of GVC on embodied emissions. Third, discussions about the impacts of GVC on EEIT in previous studies were mainly focused on the emitting country, and econometric analysis was primarily used to obtain qualitative results. Since carbon emission reduction is a global task, the impacts of EEIT and GVC on global emissions also need more attention. In addition, quantitative results are also significant for global emission reduction, and quantitative results are difficult to obtain using only econometric analysis.

Given this, the main contributions of this paper are as follows. First, trade-in value-added accounting and the gross export decomposition framework were adopted in this paper. Taking China as an empirical case, we accurately identified the final destinations of China’s embodied emission exports and the sources of China’s embodied emission imports. Second, our methodology divided routes according to the border crossings of intermediate inputs in exports and separated out the exports based on the gross export decomposition framework. This measure can distinguish the embodied emission transfer destinations and concurrently consider the transfer process and GVC embedding position. From this route-based perspective, this study reassessed China’s EEIT, focusing on the domestic emissions transfer process after exporting. Third, the balance of avoided emissions (BAE) was adopted and improved in combination with our GVC-based route analysis to assess the impact of China’s foreign trade on global carbon emissions.

The remainder of this paper is organized as follows: the “Methodology and data” section provides the methodology and data sources. The “Results and discussion” section presents the basic results of China’s EEIT characteristics and further discussions about the impacts of China’s EEIT on global emissions. The “Conclusion and policy implications” section presents the conclusions and policy implications.
Methodology and data

Methodology

Embodied emissions are most commonly measured using multi-region input–output (MRIO). Appendix 1 provides the basic framework in Table 6 and calculations.

A country’s exports can be completely decomposed into 16 components according to Wang et al.’s decomposition framework (Wang et al. 2014). This decomposition framework contributes significantly to GVC theory and the trade-in value-added accounting system. Following Wang’s decomposition framework, Fei et al., Zhang et al., and Bai et al. decomposed a country’s bilateral exports into 17 terms (Fei et al. 2020; Zhang et al. 2021a; Bai et al. 2022). Zhang et al. decomposed the energy use embodied in a country’s trade-in value-added accounting system. Following Wang’s framework contributes significantly to GVC theory and the transition framework (Wang et al. 2014). This decomposition framework is global Leontief inverse matrix of country \( s \) to country \( r \), representing the direct input of country \( s \) to produce a unit of final use of country \( r \). \( B^s \) is the submatrix of the global Leontief inverse matrix of country \( r \). \( Y^s \) is domestic final use of country \( r \).

\[
DEM2^s = (F^s L^s)^T \# (A^s B^s Y^s) \quad (2)
\]

DEM3: Domestic emissions embodied in intermediate exports to the direct importer are used to produce exports to the third party and are finally absorbed by the direct importer. Where \( t \) represents the third party and “\( \sum \)” refers to the sum of all third parties involved in the trade.

\[
DEM3^s = (F^s L^s)^T \# (A^s \sum_{t, r \neq s} B^r Y^s) \quad (3)
\]

DEM4: Domestic emissions embodied in intermediate exports to direct importers to produce final exports to third parties, where \( u \) refers to the fourth party involved in the trade.

\[
DEM4^{s-t} = (F^s L^s)^T \# (A^s B^t Y^s) \quad (t \neq s, r) \quad (4)
\]

DEM5: Domestic emissions embodied in intermediate exports to direct importers to produce intermediate exports to third parties for their domestic final consumption production. Where \( u \) refers to the fourth party involved in the trade.

\[
DEM5^{s-t} = (F^s L^s)^T \# (A^s B^t Y^s) \quad (t \neq s, r) \quad (5)
\]

DEM6: Domestic emissions embodied in intermediate exports to direct importers to produce intermediate exports to third parties for their export production (except for upstream suppliers), where \( u \) refers to the fourth party involved in the trade.

\[
DEM6^{s-t-u} = (F^s L^s)^T \# (A^s \sum_{t, r \neq s} B^r Y^u) \quad (u \neq s, r, t) \quad (6)
\]

\[
DEM6^s = \sum_{u \neq s, r, t} DEM6^{s-t-u} \quad (9)
\]

The gross value of domestic emissions that are finally absorbed abroad can be calculated as:

\[
DEM = \sum_s DEM^s
\]

\footnote{This study focuses on the domestic emissions absorbed abroad. The calculations of foreign emissions embodied in exports (FEM) and emissions embodied in exports and finally returned home (RDEM) are provided in Appendix 2.}
According to Eq. (10), the gross DEM can be divided into two parts (absorbed in the direct trade partner, i.e., $r$ in this model, and absorbed in indirect trade partners, i.e., $t$ and $u$ in this model). To distinguish the actual final destination and calculate accurate emission transfer, we calculated the embodied emissions absorbed by all indirect trading partners separately according to the final destination, referring to Eqs. (4), (6), and (8). This measure solves the ambiguity of the final destinations caused by taking the gross value of all indirect partners as one item in previous studies.

So far, we have decomposed the total emissions embodied in a country’s bilateral exports (exports from $s$ to $r$ in the model). According to Eqs. (1)–(10), the gross emissions embodied in exports are initially emitted from different sources and finally absorbed in various destinations. Calculations based on traditional gross value accounting commonly generate the sum of $FEM$, $RDEM$, and $DEM$, which fail to distinguish the sources and destinations and thus cannot represent the real embodied emission export. Only $DEM$ is the emission initially emitted domestically and is finally absorbed abroad, depicting the actual emission export. And Meng claimed that this index is the only emission trade measure consistently associated with bilateral gross trade flows (Meng et al. 2018).

Given that GVC refers to the participation of two or more countries in production, the significance of GVC lies in the cross-border flows of intermediate products. Unlike the commonly used evaluation indicators of a country’s position in GVC (i.e., GVC participation index and production length), this study focuses on the foreign downstream production stages of exported goods. Therefore, we divided the DEM transfer process into five routes according to the final absorption place and the border-crossing number of intermediate products. When the number of border crossings of the intermediate products was zero, we defined the trade route as a “onefold value chain route.” When intermediates cross the border once, we defined the trade route as a “simple GVC route.” When the border crossing number is two or more, we defined the trade route as a “complex GVC route.” Specifications are listed in Table 1. As Wang et al. claimed, the greater the number of downstream production stages, the more upstream side of the production chain the input is (Wang et al. 2017). We can infer that the more complex GVC export routes (routes 3 and 5) mean that the exporter stands at a higher position in the global production chain.
Table 1 Definition of routes and corresponding calculations

| Route   | Value chain type | Final destination | Calculation | Intermediate cross-border times | Specifics |
|---------|------------------|-------------------|-------------|---------------------------------|-----------|
| Route 1 | Onefold value chain | Direct            | DEM1        | $F \rightarrow r$                |           |
| Route 2 | Simple GVC       | Direct            | DEM2        | $s \rightarrow r$               |           |
| Route 3 | Complex GVC      | Direct            | DEM3        | $s \rightarrow r \rightarrow F \rightarrow r$ |           |
| Route 4 | Simple GVC       | Indirect          | DEM4        | $s \rightarrow r \rightarrow F \rightarrow r$ |           |
| Route 5 | Complex GVC      | Indirect          | DEM5+DEM6   | 2 or more ($s \rightarrow r \rightarrow F \rightarrow r$) |           |

In the column of final destination, “Direct” and “Indirect” refer to direct trade partner ($r$ in the model) and indirect trade partners ($t$ and $u$ in the model). “F” and “I” refer to final and intermediate exports.

In theory, the statistics in the opposite direction of exports are imports. The methodology of this study is based on the decomposition framework of a country’s total exports; thus, we can analyze the source and destinations of each sector’s total export embodied emissions in a country. However, for the importer, we can only obtain the results of the emissions embodied in the importer’s industry-wide imports from a specific sector of the exporters. Therefore, in this study, all the analyses on import embodied emissions were conducted at the national level and cannot be carried out at the sectoral level.

Econometric analysis is commonly used to distinguish the relationship between trade and emissions when weighing the impacts of trade on emissions in previous studies. Zhang et al. and Ostic et al. used this method to investigate the impacts of international trade and foreign direct investments on carbon emissions in OPEC and belt and road countries and obtained reliable results (Zhang et al. 2021b; Ostic et al. 2022). However, the results obtained are qualitative. To obtain quantitative results, we adopted the balance of avoided emissions (BAE) to examine the impact of a country’s foreign trade on global emissions. According to López et al., in a 2-country model, BAE is calculated using the export embodied emissions minus emissions avoided by imports, as in the following equation (López et al., 2013a):

$$BAE_{s-r}^{1-2} = EEX_s - EAM = (\varepsilon_1 E_1 + \varepsilon_2 E_2) - (\varepsilon_1 M_1 + \varepsilon_2 M_2)$$

where $BAE_{s-r}^{1-2}$ refers to the BAE induced by bilateral trade between the two countries, and $\varepsilon_1$ and $\varepsilon_2$ refer to each country’s direct emissions coefficients. $E_1, E_2, M_1,$ and $M_2$ represent the exports and imports of the two countries, respectively.

This model was subsequently extended to multi-region models and GVC analyses (López et al. 2013b; Zhang et al. 2017). This study gives the equations of BAE induced by the foreign trade between countries $r$ and $s$ based on the combination of previous studies and proceeding route-based decompositions, specifically as follows:

$$BAE_{s-r}^{s-r} = EEX_s^r + EEX_r^s - (EAM_s^r + EAM_r^s)$$

$$= (EEX_s^r - EAM_s^r) + (EEX_r^s - EAM_r^s)$$

(12)

where $EEX_s^r$ and $EEX_r^s$ are the DEMs of the two countries, respectively. $EAM_s^r$ and $EAM_r^s$ correspond to emissions avoided by the imports of these two countries. $BAE_{s-r}^{s-r}(s)$ is the BAE induced by foreign trade of country $s$, while $BAE_{s-r}^{s-r}(r)$ is the BAE caused by country $r$, and the details are as follows:

$$BAE_{s-r}^{s-r}(s) = EEX_s^r - EAM_r^s$$

$$= \begin{cases} 
(F[L]_r)^T [(Y^s - Y^r) + (F[L]_s)^T [(A^{s-g} B^{g} Y^r) - (A^{s-g} B^{g} Y^s)]] 
\text{(Route 1)} \\
(F[L]_r)^T [(A^{r-g} B^{g} Y^r) - (A^{r-g} B^{g} Y^s)] 
\text{(Route 2)} \\
(F[L]_r)^T [(A^{r-g} B^{g} Y^r) - (A^{r-g} B^{g} Y^s)] 
\text{(Route 3)} \\
(F[L]_r)^T [(A^{s-g} B^{g} Y^s) - (A^{s-g} B^{g} Y^s)] 
\text{(Route 4)} \\
\end{cases}$$

(12.1)
The MRIO tables were derived from the World Input–Output Database (Timmer et al. 2015). The world input–output tables released in 2016 cover 43 economies and the “rest of the world region” (RW) for the years 2000 to 2014 (specifics refer to Table 7 in Appendix 3). The corresponding carbon emission data were obtained from the Joint Research Center of the European Commission (Cor-satea et al. 2019). This study decomposes China’s gross export embodied emissions to other countries and regions covered in the world input–output table for the period 2000–2014. To analyze the situation at the sector level, we merged the 56 sectors in the world input–output tables into eight industries according to the industry-intensive category, as shown in Table 2. The details are listed in Table 8 in Appendix 3.

### Results and discussion

#### Characters of China’s DEM at the sectoral level

Figure 2 shows the gross value of China’s DEM (domestic emissions absorbed abroad) and its sector structure. During the study period, China’s total DEM increased from 662.16Mt in 2000 to 2088.21Mt in 2014, peaking at 2192.55Mt in 2007. The DEM dominates China’s gross export embodied emissions which account for over 90%, accompanied by a slight decline with some fluctuation (referring to Fig. 7 in Appendix 2). The PRS and HEPO shares were the smallest and declined continuously. This decline was mainly due to the restructuring of China’s export product mix, with the share of total exports declining in these two sectors. Manufacturing accounts for over 70% of the total DEM. KIM accounted for the most significant and growing share and nearly half of the total DEM in the late study period. The CIM ranked second and experienced a decrease-to-increase trend, and the LIM followed a fluctuating downward trend. The services (except for HEPO) had an ever-changing share of approximately 20%. CIS was the most significant, followed by LIS, and KIS accounted for only a small percentage. The share of each sector analyzed here is mainly determined by China’s export structure and the domestic carbon emission intensity of each sector’s products.

The dominant position of KIM is primarily due to China’s export structure since KIM includes the manufacturing of electrical equipment and products, machinery equipment and products, and chemical industries, all of which account for a large proportion of China’s exports. CIM mainly includes manufacturing food and tobacco products, paper products, coke and refined petroleum products, rubber

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Table 2: Sector industry-intensive type and abbreviations

| Abbreviations | Sectors | Abbreviations | Sectors |
|---------------|---------|---------------|---------|
| PRS           | Primary and natural resources sectors | CIS      | Capital-intensive service |
| CIM           | Capital-intensive manufacturing | LIS      | Labor-intensive service |
| LIM           | Labor-intensive manufacturing | KIS      | Knowledge-intensive service |
| KIM           | Knowledge-intensive manufacturing | HEPO     | Health/education/public service/other services |

\[ BAEmr(r) = EExr - EAmr \]

\[
= \left( F^r B^\gamma \right) y \left( [Y^r - Y'^r] \right) \\
+ \left( F^r L^\gamma \right) y \left( [A^r B^\gamma Y'^r] - (A^r B^\gamma Y'^r) \right) \\
+ \left( F^r L^\gamma \right) y \left( [A^r \sum_{s \neq s} B^\gamma Y'^s] - (A^r \sum_{s \neq s} B^\gamma Y'^s) \right) \\
+ \left( F^r L^\gamma \right) y \left( [A^r B^\gamma \sum_{s \neq s} Y'^s] - (A^r B^\gamma \sum_{s \neq s} Y'^s) \right) \\
+ \left( F^r L^\gamma \right) y \left( [A^r \sum_{s \neq s} B^\gamma Y'^s] - (A^r \sum_{s \neq s} B^\gamma Y'^s) \right) \\
+ \left( F^r L^\gamma \right) y \left( [A^r \sum_{s \neq s} B^\gamma Y'^s] - (A^r \sum_{s \neq s} B^\gamma Y'^s) \right) \\
\]

(12.2)

As Eqs. (12.1) and (12.2) show, the BAE induced by each country is driven by the direct emission intensity \( F^r \) and \( F^r \), production technology matrix \( (L^\alpha, B^\alpha, L^\gamma, \text{ and } B^\gamma) \), and the trade imbalance between the two countries. In conclusion, the BAE induced by each country is affected by its domestic production technology and foreign trade structure.

#### Data

The MRIO tables were derived from the World Input–Output Database (Timmer et al. 2015). The world input–output tables released in 2016 cover 43 economies and the “rest of the world region” (RW) for the years 2000 to 2014 (specifics refer to Table 7 in Appendix 3). The corresponding carbon emission data were obtained from the Joint Research Center of the European Commission (Cor-satea et al. 2019). This study decomposes China’s gross export embodied emissions to other countries and regions covered in the world input–output table for the period 2000–2014. To analyze the situation at the sector level, we merged the 56 sectors in the world input–output tables into eight industries according to the industry-intensive category, as shown in Table 2. The details are listed in Table 8 in Appendix 3.
and plastic products, non-metallic mineral products, basic metals, and fabricated metal products. These sectors only accounted for a small proportion of China’s exports, except for basic metal and metal products. Thus, the high rank of CIM was mainly driven by the high emission intensity of these sectors. Although LIM held a higher proportion of total exports than CIM, its share was lower than that of CIM, indicating that the domestic emission intensity of LIM is lower than that of CIM. This difference is determined by the total emission intensity of each sector and its domestic emission share. The total emission intensity is relevant to the product’s characteristics; for example, the light industrial products included in the LIM have low emission intensity. The sector’s domestic emission share is closely related to its position in the value chain, i.e., the installation of machinery and equipment sectors included in the LIM. This type of processing trade is located in the downstream stage of the value chain, with a small proportion of domestic emissions, causing the LIM sectors to contribute less to the overall DEM.

The analysis thus far shows that GVC-based export embodied emission studies are different from previous gross value studies. One of the advantages is the accurate identification of the composition of total export embodied emissions. As mentioned in the introduction, the GVC-based research framework can also track the transfer routes of embodied emissions in detail, which is the focus of this study. We can analyze the route-based results from two aspects: on the one hand, the five routes in this study represent five specific transfer modes; on the other hand, the combination of different routes can represent the result with different emphasis. For example, according to the trade pattern, route 1 represents the final goods trade, and routes 2–5 represent the intermediate goods trade. In terms of absorption destinations, routes 1–3 represent absorption by direct trade partners, while routes 4–5 represent absorption by indirect trade partners. According to the complexity of the value chain of the production process, route 1 is pure domestic production; routes 2 and 4 are simple GVC routes; routes 3 and 5 are complex GVC routes.
Figure 3 shows the export route structure of each sector’s DEM. As reported in the figure, the overall route structure of China appears to be relatively stable, with about half in route 1, followed by routes 2, 5, and 4. Route 3 ranked the last with a small portion. In general, China exports domestic emissions in the form of final goods, different from the global trade form, which is mainly driven by intermediate exports. However, at the sector level, the route structure of each sector varied greatly and changed over time. Overall, the ranking order of route structures of LIM, KIM, and HEPO (except 2005) was the same as that of the national level; route 1 accounted for a large part, followed by routes 2, 5, 4, and 3. However, the sequences of CIM, CIS, LIS, and KIS differed, with route 2 accounting for the most significant proportion, followed by routes 1, 5, 4, and 3. The route structure of the PRS changed the most during the study period. Since routes 1 and 2 accounted for the vast majority, the route structures of sectors were mainly shown in the difference between routes 1 and 2. This is primarily determined by the model of China’s export production. As for KIM and LIM, China mainly participates in their export production in the form of processing exports, so final exports dominate in these sectors. While in other sectors, China’s role is often as an initial resource provider. Thus, intermediate exports account for more in these sectors.

From the perspective of time-series changes, the leading structural transformation occurred between routes 1 and 2, and the proportion changes of other routes were relatively insignificant. Direct trade partners absorbed over 80% of the embodied domestic emissions for all sectors from route combinations. LIM and KIM exported more domestic emissions through final trade, with a slight decrease in the proportion. This was because China adopted extensive economic growth driven by processing exports and adjusted the export structure in the late study period. Simultaneously, other sectors preferred intermediate trade (a time-series result of the final trade share for each sector refers to Fig. 8 in Appendix 4). Except for LIM and KIM, which mainly produce exports purely domestically, most sectors export domestic embodied emissions through a simple GVC route. The complex GVC route accounted for approximately 10% of the total value.
Characters of China’s embodied emission exports and imports at the route level

All the above analyses at the sectoral level are the results of China’s export embodied emissions. We can simultaneously analyze the emissions embodied in exports and imports only at the national level. Figure 4 shows the route structures of China’s embodied domestic emissions exports and embodied foreign emission imports. The chart with the red line represents the net exports of embodied emissions; that is, the difference between domestic emissions embodied in exports absorbed abroad and foreign emissions embodied in imports absorbed domestically. The line chart shares the left coordinate axis with the accumulation chart of domestic embodied carbon export through each route. The significant imbalance between China’s domestic embodied emission exports and foreign embodied emission imports stands out in the figure. As we can see in the line chart, the net export value of embodied emissions (i.e., domestic emission exports minus foreign emissions imports) is consistent with the total domestic emissions exported by China. It showed a rapid upward trend before 2007, a rapid decline and a rapid rebound before and after the global financial crisis, and a slow decline after 2011. The total foreign emissions imports showed an unbroken and slow upward trend throughout the study period. The vast surplus between embodied emission exports and imports proves China’s role as a net exporter of embodied emissions. It is also in line with the fact that China exports high-carbon-intensive products and imports low-carbon-intensive products. The imbalance of the total value between embodied emission exports and imports is not the only focus; there are significant differences in the route structure between emission exports and imports. Route 1 accounted for a dominant position for embodied domestic emission exports, with a share of over 50% of the gross value (except in 2014, with a slight difference). This was mainly because of the large proportion of processing trade in China. Route 2 was ranked second, accounting for over 30%. Routes 5 and 4 held similar proportions, approximately 5–7%, and the former had a slightly higher share. Route 3 accounted for only a small proportion. As for foreign emission imports, route 2 dominated the route structure, with a share of approximately 60%. Route 1 accounted for approximately 20%, with a general trend from upward to downward. Route 4 accounted for approximately 5–6%, while route 5 accounted for twice.

It should be noted that the concept of the net export of embodied emissions in this study is different from the net exports in previous studies. In previous studies, net export embodied emissions were usually based on gross value accounting and equaled the total value of export embodied emissions minus import embodied emissions. In this study, the net exports of embodied emissions emphasize their source and final consumption destinations. Embodied...
emissions can clearly be defined as exports or imports only when the source and final sink differ.

It is not comprehensive to analyze China’s foreign trade embodied emissions only from the quantitative characteristics, and emission intensity is a beneficial index for measuring the relationship between economic benefits and carbon emissions. This study uses export embodied domestic emissions absorbed abroad and export embodied domestic value-added to calculate the domestic embodied emission intensity. This embodied emission intensity can be interpreted as the domestic emission required to create a unit of domestic value-added benefit through exports. Similarly, this study also calculated the import embodied foreign emission intensity. Figure 5 shows the results of the domestic embodied emission intensity based on the routes. Since sector-level analysis can only be applied to exports, we provide the results of China’s export embodied domestic emission intensity by sector, referring to Fig. 9 in Appendix 4.

From the overall level, two results stand out in the figure: China’s export embodied domestic emission intensity was much higher than the import embodied foreign emission intensity; China’s export embodied domestic emission intensity dropped sharply. The significant difference between imports and exports indicates that China has effectively replaced some domestic production of products that may generate more emissions if produced domestically through imports. It follows that China’s aggressive expansion of imports in recent years has indirectly contributed to global emission reduction. For both exports and imports, the intensities of route 1 were the lowest among the five routes. The sequences of the other four routes differed between exports and imports. For export, the line charts in green and blue overlapped most of the time, indicating that the export embodied domestic emission intensities of routes 2 and 3 were almost the same during the study period. The intensity of route 5 was also practically the same as that of routes 2 and 3 after 2004; however, it was apparently higher than the intensity of route 4 throughout the study period. Route 2 was the highest for imports during the entire study period, followed by route 3. The intensity of route 5 was higher than that of route 4 before 2007, and the trend reversed after that.

Fig. 5 Import and export embodied emission intensity of each route. Notes: the insert on the top right corner is the value of 2014, and its unit is also kg/dollar. Taking the export embodied domestic emission intensity of route 1 as an example, the value is 0.99 kg/dollar, indicating that China needs to emit 0.99 kg of domestic emissions to meet foreign consumption to create 1 dollar of domestic value-added through export in route 1 mode.
emissions and the value-added embodied in them. In other words, the differences among the domestic embodied emission intensities of routes 2 to 5 are mainly driven by the export structure of intermediate products in different export routes. Different export routes indicate intermediate goods’ positions in the production chain when they are exported. The more complex the GVC of the export route, the more subsequent production processes, and the closer the exporters are to the upstream of the production chain. Suppose the upstream production process belongs to R&D products with high value-added and low emissions. In that case, its embodied domestic emission intensity should be very low. However, it is evident from Fig. 5 that the embodied domestic emission intensity of China’s complex value chain exports, namely routes 3 and 5, is not the lowest among the four routes. However, the intensity of route 5 is significantly higher than that of route 4, indicating that the upstream intermediate products of China’s exports tend to be more resource-input with higher emissions than R&D products. The more complex the GVC of import routes, the lower the intensity, indicating that China’s imports have more R&D products.

**Further discussion on global impacts**

The empirical results provide the characteristics of China’s foreign trade embodied emissions based on GVC accounting and route analysis. This section further discusses the impact of China’s foreign trade on global emissions.

Figure 6 shows the BAE results of China’s foreign trade through five routes. The figure quantifies the impact of China’s foreign trade through five routes on global emissions. The results show that China’s foreign trade consistently increased global emissions during the study period, and the impact peaked in 2007. From a route perspective, the impact of each route varied. Trade through route 1 increased the largest volume of global emissions, dominating the trend of the total impact, and the value of route 1 was larger than the gross value. Considering route 1 represents the final trade, while other routes represent intermediate trade, this result shows that China’s final trade increased global emissions, while intermediate trade reduced global emissions. Among the four intermediate trade routes, routes 2 and 4, which we defined as simple GVC routes, decreased the global emissions for most of the study period. In contrast, routes 3 and 5, complex GVC routes, increased global emissions all the time. The global emissions increased by routes 3 and 5 were less than those reduced by routes 2 and 4, i.e., GVC-related trade of China promoted global emission reduction. This result proves to some extent that globalization promotes global emission reduction.

Table 3 shows the route-based BAE induced by China and its trading partners. As mentioned in the “Methodology” section, the BAE induced by China is primarily influenced by China’s domestic production technology and foreign trade structures. Generally, the BAE caused by each trade partner has an opposite sign (i.e., a positive or negative value) in

![Fig. 6 Route-based impact of China’s foreign trade on global emissions. Notes: The bar graphs in the figure show the BAE of China’s trade through each route, indicating the impacts on global emissions, for an increase in positive value and a decrease in negative value. The red line chart in the figure shows the gross value of BAE in these five routes](image)
bilateral trade because a country’s production technology (i.e., carbon emissions per unit of output) is usually positive. Therefore, the positive and negative situations of the BAE caused by each trade partner depend on the positive and negative status of the surplus of the country’s exports and imports. As shown in Table 3, China’s trade through routes 1, 3, and 5 increased global emissions, while routes 2 and 4 decreased global emissions. This result indicates that China had a trade surplus through routes 1, 3, and 5 and a deficit in routes 2 and 4. Combined with the results in Fig. 6, it can be seen that the positive and negative status of the total impact of China’s trade on global emissions is consistent with the positive and negative relationship of the BAE caused by China. This result indicates that under the condition that the values of the imbalance between exports and imports are equal and the plus-minus signs will be reversed, China’s domestic production intensity is higher than its import production intensity, and this information is consistent with Fig. 5.

It is generally believed that countries in the upper position of GVC tend to export products with high value-added and low emissions. However, China’s complex GVC (in routes 3 and 5) export embodied emission intensities were not significantly lower than other routes, as shown in Fig. 5, inconsistent with this inference. At the same time, China’s imports are broadly consistent with the inference. Given this, China’s move to enlarge its imports in recent years has positively impacted global emissions reduction. In terms of exports, China’s technological advances and optimizations in its foreign trade structure in recent years have allowed it to reduce global emissions through complex GVC in its bilateral trade with some countries.

Table 4 shows the BAE results for China’s bilateral trade with other countries and regions from 2000 to 2014. As shown in the table, China’s bilateral trade with Australia, Brazil, and Korea has decreased in most years during the study period. In particular, China-Korea trade contributed to global emission reduction throughout the study period, with a cumulative reduction of 634.86Mt. Bilateral trade with Canada, the European Union, Mexico, and the USA had consistently increasing global emissions, with a cumulative increase of 4045.79Mt, accounting for over 85% of the total cumulative increase in global emissions caused by China’s foreign trade during the study period.

However, there are also differences in the impact on global emissions among the routes within each bilateral trade. Table 5 presents the route-based results for China’s bilateral trade with each trade partner in 2014. The results suggest that even if bilateral trade increases global emissions overall, there may still be ways to reduce global emissions through some routes. For example, bilateral trade with Brazil and Japan through global value chain routes reduced global emissions despite the overall increase in global emissions. China-Australia bilateral trade had a decrease in global emissions, while its trade through route 1 (final goods trade) had the opposite impact when compared to other routes. Moreover, when taken as a whole, these bilateral trades fall into four categories (except for region RW in the table). Specifically, bilateral trade with the USA, Mexico, the European Union, and Canada increased global emissions through all...
routes, and these are the top four trade partners contributing to global emissions. Bilateral trade with Australia, Brazil, and Japan through route 1 increased global emissions and decreased emissions through other routes. Bilateral trade with India and Korea showed the opposite results. China-Russia bilateral trade differs from other bilateral trades, and only trade through route 5 could reduce global emissions. Overall, China’s export trade did not break away from the negative impact on global emissions reduction during the study period; however, these results demonstrate the feasibility of reducing global emissions by adjusting the structure of China’s bilateral trade with different countries.

In previous studies, GVC participation, measured by the proportion of foreign components in total exports, was used to calculate the extent of China’s participation in the global division of labor. The results generally indicate that China’s position in the GVC was climbing. Their regression analyses of GVC participation and China’s per capita emissions or export embodied emissions concluded that China’s GVC participation reduces emissions (Wang et al. 2019; Zhang et al. 2020). Participation in the GVC assuredly enables a country to benefit from the technology spillover effect and improve domestic technology. Moreover, the fierce competition of the international division can, in turn, force domestic innovation and enhance the country’s production efficiency. However, participating in global production also stimulates growth. It drives more emissions, especially when a country lacks comparative advantages in high-end technology production stages.

China participated in GVC in processing trade from the beginning, engaging in processing manufacturing and other low value-added production stages. At the same time, developed countries occupied the R&D stages, critical components, special materials, and high value-added production stages. This kind of GVC embedding may form the “low-end locking” in the value chain, which is not conducive to China’s position climbing in the global division of labor. In addition, from the perspective of emission reduction, “low-end locking” hinders the improvement of China’s emission reduction technology, harming global emission reduction.

To assess the impact of China’s foreign trade on exports embodied emissions and even global emissions only from the perspective of participation has neglected the impact of China’s positions in the production process. According to the results, on the whole, China’s export production has not gotten rid of the “low-end locking” dilemma during the study period; however, these results demonstrate the feasibility of reducing global emissions by adjusting the structure of China’s bilateral trade with different countries.

### Table 4
| Year | AUS | BRA | CAN | EU  | IND | JPN | KOR | MEX | RUS | RW | USA | Gross |
|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|----|-----|-------|
| 2000 | -0.11 | -0.11 | 5.34 | 27.72 | -0.21 | 16.24 | -19.17 | 3.35 | 5.76 | -17.00 | 77.84 | 99.64 |
| 2001 | -1.47 | -0.42 | 4.78 | 18.62 | 0.48 | 17.82 | -16.19 | 4.13 | 5.73 | -13.35 | 72.01 | 92.14 |
| 2002 | -0.59 | -1.08 | 8.23 | 18.57 | 0.05 | 10.53 | -20.81 | 6.24 | 5.66 | -8.12 | 98.30 | 116.97 |
| 2003 | 0.08 | -3.20 | 12.73 | 28.39 | -1.20 | 6.83 | -34.19 | 7.37 | 4.98 | -3.95 | 130.82 | 150.47 |
| 2004 | 2.71 | -1.83 | 18.59 | 50.16 | -0.32 | 9.55 | -51.88 | 12.12 | 3.04 | 15.65 | 173.78 | 231.56 |
| 2005 | 1.49 | -1.98 | 26.40 | 97.33 | 0.28 | 25.87 | -56.67 | 14.07 | 4.85 | 32.05 | 238.93 | 382.62 |
| 2006 | 2.11 | 0.13 | 30.80 | 125.09 | 3.47 | 15.07 | -49.60 | 21.65 | 5.52 | 104.63 | 259.26 | 518.12 |
| 2007 | 0.83 | 1.20 | 31.54 | 139.74 | 7.83 | 8.16 | -42.78 | 21.95 | 10.95 | 163.87 | 244.41 | 587.71 |
| 2008 | -2.81 | 5.12 | 27.93 | 137.58 | 4.27 | 3.68 | -37.56 | 20.21 | 10.01 | 181.37 | 196.97 | 546.76 |
| 2009 | -3.32 | -1.24 | 22.25 | 78.14 | 4.34 | -4.71 | -51.70 | 16.61 | 3.46 | 130.42 | 158.25 | 352.49 |
| 2010 | -10.26 | 2.67 | 24.87 | 93.59 | 4.31 | -14.30 | -55.16 | 21.49 | 5.79 | 114.52 | 172.64 | 360.14 |
| 2011 | -11.46 | -0.64 | 24.32 | 73.58 | 6.40 | 2.74 | -54.05 | 22.80 | 4.90 | 92.72 | 158.03 | 319.33 |
| 2012 | -5.93 | 0.77 | 24.50 | 53.24 | 4.46 | 20.49 | -50.76 | 21.36 | 4.97 | 96.11 | 159.81 | 329.03 |
| 2013 | -19.04 | 4.53 | 22.74 | 73.34 | 1.30 | 22.24 | -48.13 | 20.83 | 6.89 | 74.90 | 145.82 | 305.43 |
| 2014 | -9.57 | 7.37 | 24.09 | 51.41 | -0.29 | 20.92 | -46.22 | 21.14 | 3.23 | 136.10 | 148.00 | 356.19 |

### Table 5
| Year | AUS | BRA | CAN | EU  | IND | JPN | KOR | MEX | RUS | RW | USA | Gross |
|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|----|-----|-------|
| Route 1 | 10.73 | 9.39 | 12.76 | 25.92 | -1.10 | 35.67 | -15.59 | 8.64 | 2.89 | 163.80 | 105.44 |
| Route 2 | -14.45 | -0.17 | 7.17 | 15.59 | 0.60 | -12.76 | -30.06 | 5.53 | 0.30 | -45.68 | 37.57 |
| Route 3 | -0.07 | -0.03 | 0.02 | 0.25 | 0.00 | -0.09 | -0.12 | 0.01 | 0.00 | 2.14 | 0.61 |
| Route 4 | -3.46 | -1.24 | 1.40 | 4.18 | 0.11 | -1.80 | -2.13 | 4.06 | 0.07 | -2.69 | 0.85 |
| Route 5 | -2.32 | -0.58 | 2.74 | 5.47 | 0.10 | -0.11 | 1.68 | 2.91 | -0.03 | 18.53 | 3.53 |
| Gross | -9.57 | 7.37 | 24.09 | 51.41 | -0.29 | 20.92 | -46.22 | 21.14 | 3.23 | 136.10 | 148.00 |
period. The breadth of participation in GVC (namely, the GVC-related trade in total international trade) is increasing for China. However, the depth of GVC participation (the leading role in GVC) still needs to be enhanced. Enhancing the competitiveness of high-end industries, especially the export of technology-intensive services, can improve China’s position in the GVC and promote global emission reduction. In recent years, international trade patterns have changed frequently. The development of the Internet, the Internet of things, and the digital economy have stimulated the GVC to evolve constantly. The impact of COVID-19 on the global economy has accelerated the restructuring of the GVC. China must take an active part in globalization through the reconstruction of the GVC to cope with the multiple pressures of domestic and international emission reduction and stable economic development.

Conclusion and policy implications

Based on the GVC decomposition model of total exports, this study proposes a route decomposition method based on the number of border-crossings of intermediate goods in total exports. The various routes can distinguish the complexity and length of the value chain of products after being exported. From the perspective of export routes, this study analyzes the characteristics of carbon emissions embodied in China’s foreign trade from 2000 to 2014. It further discusses the impact of China’s foreign trade on global emissions and the challenges China faces, and we finally draw the following conclusions.

1. During the study period, China’s total export embodied domestic emissions experienced a trend of rapid rise–temporary decline–rebound–steady, and its share in gross export embodied emissions went slightly down at the end. From the sector-level perspective, embodied domestic emission exports are mainly sourced from manufacturing sectors. Capital-intensive and labor-intensive services are the primary sources in the service industry.

2. The composition of export routes varied greatly among sectors. Still, the final goods trade (route 1) and simple GVC-related trade (route 2) occupied most. The route structure changes over time in each sector also mainly occurred between routes 1 and 2. Complex GVC routes (routes 3 and 5) accounted for a relatively small proportion and did not change significantly during the study period.

3. Route 1 accounted for most of China’s domestic embodied emission exports. Route 2 accounted for a large proportion. Foreign embodied emissions imports were dominated by route 2. Route 1 was the lowest among the five routes in China’s imports and exports in terms of intensity. For the remaining four GVC routes, import trade generally conforms to the traditional perception that the more complex the value chain, the lower the embodied emission intensity. However, this perception did not match China’s exports since China’s complex GVC exports mainly tended to be a resource-input type. China’s expansion of imports during the late study period significantly contributed to reducing global emissions.

4. China’s foreign trade consistently increased global emissions during the study period, and its impact peaked in 2007. Trade through route 1 increased the largest volume of global emissions, dominating the trend of the total impact. Complex GVC trade (routes 3 and 5) has also increased global emissions all the time. Simple GVC trade (routes 2 and 4) decreased global emissions for most of the study period. GVC-related trade generally decreased global emissions, proving that globalization can promote global emission reduction to some extent. The feasibility of reducing global emissions exists by adjusting the structure of China’s bilateral trade with different countries.

China’s foreign trade structure, particularly its export trade, contributes to global emissions growth, albeit at a diminishing rate. It is urgent to change China’s “low-end locking” dilemma in GVC and its role as a resource provider in complex GVC exports. The impact of the new international trade pattern, digital economy, and COVID-19 has stimulated the restructuring of the GVC. Key insights arising from the findings of this study are that China should actively participate in globalization by upgrading its GVC and promoting its position in global production in response to the multiple pressures it faces (domestic carbon–neutral targets, international action on climate change, and stable economic growth). Implications that the policymakers should consider are discussed below.

First, manufacturing and capital-intensive services have always been the critical sectors for China’s embodied carbon exports and will remain so for the foreseeable future. It is urgent to decrease the emission intensity of manufacturing from the perspective of technological advancement and energy structure and efficiency. In addition, improving the structure of export products and transforming China’s role as a resource provider in export trade are also the focuses of China’s international trade transformation.

Second, as a major processing factor in global trade, China’s embodied carbon export routes are dominated by final goods trade and simple GVC trade. China embeds at the lower end of the GVC and urgently needs to strengthen the role of high-end industries in global production. Since the technological competitiveness gap between China and developed countries is gradually narrowing, China should strengthen basic scientific research and promote independent
innovation to enhance overall technological competitiveness in globalization and promote its position in the low-end value chain of global production.

Besides, in the long run, China should adhere to supply-side reform and continue to improve its domestic supply chain network. While promoting domestic industrial upgrading, China should also improve the investment environment of domestic enterprises and attract high-quality production factors to converge in China.

Finally, China’s globalization can promote global emission reduction, but for China itself, domestic emissions increased. Combined with the new development pattern of “dual circulation” in the future, China should firmly embed itself in the global division of labor and simultaneously lead low-emission-intensive value chains. China should unite all countries to adhere to the in-depth development of globalization and fully use domestic and international markets, optimizing the allocation of global resources and each country’s comparative advantages to reduce domestic emissions while promoting global emission reduction.

Appendix 1

Multi-region input–output (MRIO) is most commonly used to measure embodied emissions. A fundamental MRIO framework is provided in Table 6:

According to the basic input–output model, all gross output of country \( s \) must be used as either intermediate goods or final goods at home or abroad:

\[
X^s = A^{rs}X^r + Y^{rs} + \sum_{r \neq s} G^{rs}X^r + \sum_{r \neq s}^{G} Y^{rs} \quad (13)
\]

where \( X^s \) refers to gross output of country \( s \). \( A^{rs} \) is the direct input coefficient matrix, and each of its elements \( (a_{ij}) \) refers to the sectors 1 … \( N \) equals the corresponding intermediate consumption \( (z_{ij}) \) divided gross input \( (x_i) \), \( a_{ij} = z_{ij} / x_i \). \( Y^{rs} \) denotes the final use in country \( r \) of goods produced in country \( s \). Stated in matrix form as:

\[
\begin{bmatrix}
X^s \\
\vdots \\
X^G \\
\end{bmatrix} =
\begin{bmatrix}
A^{rs} & \cdots & A^{rG} \\
\vdots & \ddots & \vdots \\
A^{Gr} & \cdots & A^{GG} \\
\end{bmatrix}
\begin{bmatrix}
X^r \\
\vdots \\
X^G \\
\end{bmatrix}
+ \begin{bmatrix}
Y^{rs} + \sum_{s \neq r} G^{rs} Y^{rs} \\
\vdots \\
Y^{Gs} + \sum_{s \neq r}^{G} Y^{Gs} \\
\end{bmatrix}
\quad (14)
\]

With rearrangement, we can obtain the following:

\[
\begin{bmatrix}
X^s \\
\vdots \\
X^G \\
\end{bmatrix} =
\begin{bmatrix}
I - A^{rs} & \cdots & -A^{rG} \\
\vdots & \ddots & \vdots \\
-A^{Gr} & \cdots & I - A^{GG} \\
\end{bmatrix}
\begin{bmatrix}
Y^{rs} + \sum_{s \neq r} G^{rs} Y^{rs} \\
\vdots \\
Y^{Gs} + \sum_{s \neq r}^{G} Y^{Gs} \\
\end{bmatrix}
= \begin{bmatrix}
B^{rs} & \cdots & B^{rG} \\
\vdots & \ddots & \vdots \\
B^{Gs} & \cdots & B^{GG} \\
\end{bmatrix}
\begin{bmatrix}
Y^s \\
\vdots \\
Y^G \\
\end{bmatrix}
\quad (15)
\]

where \( B^{rs} \) is the total requirements matrix, which gives the total requirement to produce a unit of gross output of country \( r \) needed from country \( s \). \( Y^s \) is the gross final goods produced in country \( s \), composed by domestic use \( Y^{ss} \) and abroad use \( \sum_{r \neq s}^{G} Y^{rs} \).

Direct emission coefficient matrix \( F = \begin{bmatrix} F^s & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & F^G \end{bmatrix} \), where each submatrix is the diagonal matrix of a country’s direct emission coefficient and \( F^s = \begin{bmatrix} f_{1}^s & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & f_{N}^s \end{bmatrix} \).

The elements of \( F^s \) are denoted by \( f_{j}^s = e_{mj}^s / x_j \), where \( f_{j}^s \) is the direct emission coefficient of sector \( j \) in country \( s \), and \( e_{mj}^s \) is the direct carbon emission of sector \( j \) in country \( s \). Then, we can obtain the gross direct emission vector as

\[
\begin{bmatrix}
EM^s \\
\vdots \\
EM^G \\
\end{bmatrix} = \begin{bmatrix}
F^s & \cdots & 0 \\
\vdots & \ddots & \vdots \\
0 & \cdots & F^G \\
\end{bmatrix}
\begin{bmatrix}
B^{rs} & \cdots & B^{rG} \\
\vdots & \ddots & \vdots \\
B^{Gs} & \cdots & B^{GG} \\
\end{bmatrix}
\begin{bmatrix}
Y^s \\
\vdots \\
Y^G \\
\end{bmatrix}
\quad (16)
\]

Table 6 A basic framework of a multi-region input–output table

| Intermediate use | Country | Sector | Country s | \( 1 \) … \( N \) | Country G | \( 1 \) … \( N \) |
|------------------|---------|--------|-----------|----------------|-----------|----------------|
| Intermediate input | Country s | \( 1 \) | \( Z^s_{qi} \) | \( \vdots \) | \( Z^G_{qi} \) | \( Y^{ss}_{i} \) | \( \vdots \) | \( Y^{GG}_{i} \) | \( X^i \) |
| \vdots | \vdots | \vdots | \vdots | \vdots | \vdots | \vdots | \vdots | \vdots | \vdots |
| Country G | \( 1 \) | \( Z^G_{qi} \) | \( \vdots \) | \( Z^G_{qi} \) | \( Y^{Gs}_{i} \) | \( \vdots \) | \( Y^{AGO}_{i} \) | \( Y^{G}_{i} \) | \( X^{G}_{i} \) |
| \vdots | \vdots | \vdots | \vdots | \vdots | \vdots | \vdots | \vdots | \vdots | \vdots |

Value-added \( V^s_{i} \)

Gross Input \( X^s_{i} \)

The subscripts \( i \) and \( j \) in the table denote the sector number, and \( i, j = 1, \ldots, N \)
Appendix 2

According to the decomposed framework, we can calculate the foreign emissions embodied in exports from country \( s \) to country \( r \) as:

\[
FEM^{sr} = (F^r B^{sr})^T Y^{sr} + (F^r B^{sr})^T (A^{sr} L^{sr} Y^{sr}) + \left( \sum_{t \neq r} G \right)^T Y^{sr} + \left( \sum_{t \neq r} G \right)^T (A^{sr} L^{sr} Y^{sr})
\]

(17)

where \( FEM^{sr} \) is the total emissions embodied in the exports of country \( s \) to country \( r \). \( F^r \) is the direct emission coefficient matrix of country \( r \). \( B^{sr} \) represents the submatrix of the global Leontief inverse matrix, referring to the total requirements from country \( r \) to produce a unit of total output in country \( s \). \( Y^{sr} \) is the final use of country \( r \) produced in country \( s \). \( A^{sr} \) is the direct input matrix of country \( s \) to country \( r \), referring to the direct input of country \( s \) to produce a unit of the total output of country \( r \). \( L^{sr} \) is the local Leontief inverse matrix of country \( r \). \( Y^{sr} \) is the domestic final use of country \( r \). \( F^r \) is similar to \( F^r \), and \( B^{sr} \) is similar to \( B^{sr} \). The superscript \( T \) refers to the transpose of the matrix. In the equation, (F1) is the final export embodied emissions from country \( r \) (i.e., direct trade partner); (F2) is the intermediate export embodied emissions from country \( r \); (F3) is the final export embodied emissions from all of country \( r \) (i.e., all indirect trade partners, consisting of the remaining countries and regions except for countries \( s \) and \( r \)); and (F4) is the intermediate export embodied emissions from all country \( t \).

Domestic emissions which finally return home can be expressed as follows:

\[
RDEM^{sr} = (F^r L^{sr})^T (A^{sr} B^{sr} Y^{sr}) + (F^r L^{sr})^T (A^{sr} B^{sr} Y^{sr}) + \left( \sum_{t \neq r} G \right)^T \left( \sum_{t \neq r} B^{sr} Y^{sr} \right)
\]

(18)

where \( RDEM^{sr} \) is the gross domestic emissions embodied in exports and finally returns home. In the equation, (RDEM1) is the emission that returns home through final imports from country \( r \); (RDEM2) is the emissions that return home through intermediate imports from country \( r \); and (RDEM3) is the emissions that return home through imports from all other indirect partners.

Figure 7

As this study emphasizes, not all of the carbon emissions embodied in China’s exports originate in China, nor are

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Fig. 7 China’s gross export embodied emissions and composition. Note: DEM in this figure represents domestic emissions that are finally absorbed abroad, RDEM refers to domestic emissions that finally return home, and FEM is foreign emissions embodied in China’s gross exports.
they all absorbed abroad. This study first distinguishes the sources and final destinations of all the carbon emissions embodied in China’s gross exports. The results are presented in Fig. 7. During the study period, China’s total export embodied emissions rose before the global financial crisis in 2008, especially after 2001, when China joined the WTO. After a brief dip in 2008 and 2009, gross value rebounded in the following 2 years to a slight increase in the pre-crisis level in 2011. This rate continued to decline slowly during the later study period. DEM dominated China’s export embodied emissions in terms of composition, accounting for over 90% of the total value, accompanied by a slight decline with fluctuation. FEM and RDEM accounted for a small proportion but generally showed a slow-growth trend during the study period. The rising trend of the RDEM and FEM is in line with the deepening global division of labor. The emergence and increase of RDEM indicate that an increasing number of products in China is outsourcing part of the production stages. The transformation process of the global production mode from outsourcing all production to part production stages is the process of production fragmentation and the formation of GVC. Under the irreversible trend of globalization, it is foreseeable that the proportions of RDEM and FEM will continue to increase in the future.

### Appendix 3

**Table 7** Countries and regions covered in this paper

| Country/region       | Acronym | Country/region        | Acronym | Country/region       | Acronym |
|----------------------|---------|-----------------------|---------|----------------------|---------|
| Australia            | AUS     | The European Union    | EU      | Mexico               | MEX     |
| Brazil               | BRA     | India                 | IND     | Russia               | RUS     |
| Canada               | CAN     | Japan                 | JPN     | The USA              | USA     |
| China                | CHN     | Korea                 | KOR     | Rest of the countries and regions covered in WIOT | RW |

**Table 8** Sector industry-intensive type corresponds to WIOT sector number

| Sectors                          | Corresponding sector number in WIOT | Sectors                          | Corresponding sector number in WIOT |
|----------------------------------|-------------------------------------|----------------------------------|-------------------------------------|
| Primary and natural resources sectors (PRS) | 1 ~ 4                                | Capital-intensive service (CIS)  | 24, 25, 31 ~ 35, 37 ~ 39, 44       |
| Capital-intensive manufacturing (CIM) | 5, 8 ~ 10, 13 ~ 16                    | Labor-intensive service (LIS)   | 27 ~ 30, 36, 55                   |
| Labor-intensive manufacturing (LIM) | 6, 7, 22, 23                          | Knowledge-intensive service (KIS)| 26, 40 ~ 43, 45 ~ 50               |
| Knowledge-intensive manufacturing (KIM) | 11, 12, 17 ~ 21                     | Health/education/public service/other services (HEPO) | 51 ~ 54, 56 |
Fig. 8 Share of final trade embodied emissions. Note: “Gross” in the figure refers to the national level
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