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Two sides of the same coin: The economic and environmental effects of China's international trade from a global value chain perspective

Xin Huang [a], Qi He [b,c], Zengkai Zhang [d], Kunfu Zhu [e,*]

[a] School of Economics, Xiamen University, Xiamen, China
[b] Research Institute for Global Value Chains, University of International Business and Economics, Beijing, China
[c] Laboratory for Global Value Chains, University of International Business and Economics, Beijing, China
[d] State Key Laboratory of Marine Environmental Science, College of Environment and Ecology, Xiamen University, Xiamen, China
[e] School of Economics, Renmin University of China, Beijing, China

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ABSTRACT

China's accession to the World Trade Organization (WTO) has led to rapid economic growth and international trade development. However, China is also challenged with a heavy environmental burden due to the massive carbon emissions transferred through trade. By splitting production activities into traditional trade and global value chain (GVC) activities, this paper uses an intercountry input-output (ICIO) framework to study the imbalances of the economic and environmental effects between China's imports and exports at different levels. We define the indices value added per embodied emission in imports and exports (VPM and VPX, respectively). Additionally, we find a large gap between China's VPM and VPX, primarily because developed economies gain much higher value added per embodied emission than China gained through exports in GVC activities. Then, we study how to narrow the gap between China's VPM and VPX. The application of multiplicative structural decomposition analysis (SDA) and the logarithmic mean Divisia index I (LMDI-I) approach reveals the total and bilateral-sectoral contributions of the driving factor effects to the changes in China's VPM and VPX. The results provide tailored implications for promoting the comprehensive economic and environmental benefits of China's imports and exports.

1. Introduction

The development of global production fragmentation is accompanied by the evolution of international specialization and growth in carbon emission transfers. With the leading role of multinational enterprises, advances in technology and the lowered costs of services accelerating international fragmentation (Jones and Kierzkowski, 1988; Jones, Kierzkowski, and Arndt, 2001; Los, Timmer, and de Vries, 2015), the opening up of developing economies has been another important factor facilitating North-South production sharing and reshaping international production networks (Baldwin and Lopez-Gonzalez, 2015). While developing economies have achieved economic growth and benefited from technology spillovers after embracing openness, they are challenged by a heavy environmental burden because massive emissions have been transferred from developed economies (Davis and Caldeira, 2010; Peters, Minx, Weber,

* Corresponding author at: School of Economics, Renmin University of China, Beijing 100872, China.
E-mail address: Kfzhu@ruc.edu.cn (K. Zhu).

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and Edenhofer, 2011). For developing economies, the trade-off between economic growth and environmental improvement has been an important question in need of further investigation.

As a representative gainer among developing economies, China faces a significant imbalance of the economic and environmental effects between its imports and exports, especially since its accession to the World Trade Organization (WTO). Compared to developed economies with advanced technology and leading services, China plays the role of a "pollution haven" due to its lower labor costs and looser environmental regulations (Sarkodie and Strezov, 2018; Zhang, Zhu, and Hewings, 2017). On the export side, China tends to undertake more production tasks with low value added and high carbon intensity in global production fragmentation. It has had to undertake massive carbon transfers in exports to meet downstream final demand. On the import side, developed economies have a comparative advantage in tech- and knowledge-intensive sectors, and they have advanced green technology. There is high dependence on foreign imports from developed economies to meet the domestic demand of production or consumption in China. Therefore, China tends to gain lower value added when undertaking one unit of carbon transfer in exports, and it pays higher value added when transferring one unit of carbon transfer in imports. This situation emphasizes the necessity of accelerating supply-side structural reform to improve the supply capacity and composition of exports.

This paper includes two parts to study the imbalance. First, it studies the trends of imbalances of the economic and environmental effects between China's imports and exports under an intercountry input-output (ICIO) framework. Second, by applying a multiplicative structural decomposition analysis (SDA) model, it investigates the driving factor effects on the changing trends for policy implications for promoting comprehensive economic and environmental benefits. Both parts are elaborated at the aggregate, production activity, bilateral and sectoral levels. On the one hand, policy makers may be more concerned about the heterogeneity of the benefits of exports and the payoffs of imports in different kinds of value chains. We refer to Wang, Wei, Yu, & Zhu (2022) to decompose production activities into traditional trade and GVC activities. When domestic primary inputs are used to produce a final product and are then exported, we define this value chain as a pure domestic value chain, along which only domestic value added is involved. Additionally, such activities are defined as traditional trade activities. By contrast, when domestic primary inputs are used to produce intermediate products that are exported for final production or re-exports, we define these kinds of activities as GVC activities. On the other hand, we further study the heterogeneity of value added and embodied carbon emission flows at more detailed bilateral and sectoral levels. There will be interesting potential findings, considering the fact that the net exporting destinations of China have mainly been developed economies such as the USA and Europe (Fang et al., 2021; Han, Yao, Liu, and Dunford, 2018; Wang and Ge, 2020; Zhu, Shi, Wu, Wu, and Xiong, 2018), while carbon leakages have shifted from China to other developing countries (Meng et al., 2018), such as Belt and Road Initiative countries (Lu et al., 2020).

We extend the current studies in three ways. First, we analyze the imbalance of the dual effects between imports and exports in China. We distinguish different value chain activities, trade partners and sectors to elaborate the imbalances. Second, with current studies frequently applying pollution or energy intensity (Duan and Yan, 2019; Su and Ang, 2017; Zhang et al., 2019; Zhao et al., 2017), we provide another perspective to interpret China's comprehensive economic and environmental benefits. We establish indices—value added per embodied emission import (VPM) and value added per embodied emission export (VPX)—to weight the unit carbon emission transfer in the magnitude of value added. The two indices describe the payoff of a country and its sectors when transferring unit carbon emissions through imports and the ability to gain value added when undertaking unit carbon emission transfers through exports. Third, we apply multiplicative SDA and the logarithmic mean Divisia index I (LMDI-I) approach to decompose the effects of driving factors on the increases in VPM and VPX at different levels to explore ways of narrowing the large gap between them. To provide more tailored policy implications, we reveal the bilateral-sectoral contributions of the driving factor effects on the change in VPM on backward linkages and the driving factor effects on the change in VPX on forward linkages. Therefore, we can analyze which type of final or intermediate imports lead to more value-added payoff or more carbon leakage and which type of inputs overproduce carbon emissions when producing for exports.

The remaining parts of the paper are structured as follows. Section 2 discusses the literature review. Section 3 elaborates the measurement of value added and embodied emission flows and their relative magnitude and the modeling of multiplicative SDA. The results are analyzed and discussed in Section 4. The final section provides conclusions and policy implications.

2. Literature review

To study the imbalance of economic and environmental effects between China's imports and exports, we first define our measurement of the economic and environmental effects of foreign trade as value added and embodied carbon emission flows. With the proportion of intermediate goods in global trade increasing from 51% in 2001 to 64% in 2020,[1] it is recognized that conventional gross trade statistics are inaccurate because of the double counting of value added. Accounting frameworks based on value added decomposition have been widely developed (Hummels, Ishii, and Yi, 2001; Koopman, Wang, and Wei, 2014; Los et al., 2015; Los, Timmer, and de Vries, 2016; Johnson & Noguera, 2012; Wang et al., 2022; Wang, Wei, & Zhu, 2013). For example, to bridge the gap between official trade statistics and national accounts, some scholars decompose the gross exports of a country (Koopman et al., 2014; Los et al., 2016) and bilateral exports (Wang et al., 2013) into value-added components and double-counted terms. Some scholars trace the geographical origin of value added in final products (Johnson & Noguera, 2012; Los et al., 2015; Wang et al., 2022). This paper adopts the latter approach to trace the foreign value added induced by China's final demand and the domestic value added induced by

[1] https://stats.oecd.org/Index.aspx?DataSetCode=BTDIXE_I4

foreign final demand, which are expressed as value added imports and exports, respectively. Additionally, we use embodied carbon emission flows, specifically the emissions transferred from the consumers to the producers through foreign trade, to analyze the environmental effects in a way that is consistent with the economic effects from the perspective of global value chains (GVCs), following Meng, Peters, Wang, & Li (2018).

Our paper is closely related to studies that combine the economic and environmental effects of foreign trade. Some have studied the trade-off between the dual effects of exports (Zhao et al., 2016; Zhao et al., 2017), while others have compared the difference in the dual effects of the imports and exports of a country (Duan and Yan, 2019; Yu, Feng, and Hubacek, 2014; Zhang et al., 2019). For example, Yu et al. (2014) used value added, SO_2, CO_2, land and water to study China's ecological exchange costs and found that developed economies have benefited by importing from China, while less developed economies have gained less by exporting to China. By using multiregional input-output (MRIO) tables and SO_2 data, Duan and Yan (2019) found that the pollution intensity of China's exports is much higher than that of its imports. A useful way to study the dual economic and environmental effects is to establish an index to analyze the links between them, which enables scholars to study their relative magnitude at several different levels. Su and Ang (2017) used the aggregate embodied intensity (AEI), the ratio of energy or emissions to GDP, to study comprehensive benefits at the aggregate, final demand category and sectoral levels. Zhao et al. (2017) analyzed the gap of CO_2 emissions per value added in exports between China and the USA at the aggregate and sectoral levels. Yang and Su (2019) revealed the significance of exports that drives the gap between self-aggregate carbon intensity and export aggregate carbon intensity at the global, national, regional and sectoral levels.

Another strand of studies in regard to SDA models is also closely related to this paper, in which we study the effects of driving factors on the changes in VPM and VPX and provide policy implications for improving comprehensive economic and environmental benefits. SDA has two forms, specifically, the additive form and the multiplicative form. The additive form has been extensively applied to study absolute changes, such as value added or emissions embodied in trade (Zhao et al., 2018; Li et al., 2018; Meng, Peters, et al., 2018; Wang, Li, Cai, Yang, and Wang, 2019; Zhang, Zhu and Hewings, 2017), energy use (Dietzenbacher, Kulionis, and Capurro, 2020; Lan, Malik, Lenzen, McBain, and Kanemoto, 2016) and air pollutant emissions (Luo et al., 2020; Xie, Zhao, Zhu, and Chevallier, 2018). The multiplicative form is usually applied to study the relative changes in the forms of indices (Jiang, Zhu, and Green, 2015; Su and Ang, 2017; Xia, Fan, and Yang, 2015; Zhao et al., 2017; Zhou, Zhou, Wang, and Su, 2020). For example, Su and Ang (2017) found that the emission intensity effect contributed most to the decrease in China's aggregate intensity from 2007 to 2012, as did all final demand categories except for gross fixed capital formation; Zhao et al. (2017) proposed the generalized LMDI approach and found that the IO structure effect gradually became the main reason for the difference in CO_2 emissions per value added in the exports between China and the USA from 1995 to 2009.

In this paper, we test the following expectations. First, there is a significant imbalance that has led China to pay too much value added when transferring unit carbon emissions through imports and to gain insufficient value added when undertaking unit carbon emissions through exports. Second, given the shares of intermediate goods in China's imports and exports (71% and 41% in 2014,[2] respectively) and the technology gap between China and developed economies, we expect that the large gap between China's VPM and VPX is mainly because developed economies can gain much higher value added per embodied emissions in GVC activities than China. Third, with the removal of domestic trade barriers and the improvement in production and carbon reduction technology, we expect that the domestic industry linkage effect and domestic emission coefficient effect are significant driving factors that increased VPX during the study period; however, the global industry linkage effect might be negative. Given that the import liberalization of intermediates has deepened and there is large difference among China's trade partners in carbon reduction and production technologies, we also expect that the domestic final demand effect under bilateral trade with developed and developing economies on the increase in aggregate VPM will be the opposite. Taking a step forward, we further explore the structures and relative magnitudes of the dual effects of China's imports and exports at the production activity, bilateral and sectoral levels, and decomposition and analysis at more detailed levels can help explore the in-depth reason hindering the increase in VPX and inducing the increase in VPM.

3. Methodology

3.1. Value added and embodied carbon emission flows based on the ICIO framework

Assuming that there are M countries and N sectors in a world economy, the equilibrium equation can be obtained according to the row balance:

$$\widehat{X} = A\widehat{X} + \widehat{Y} \tag{1}$$

Eq. (1) can be solved as follows:

$$\widehat{X} = (I - A)^{-1}\widehat{Y} = B\widehat{Y} \tag{2}$$

[2] https://stats.oecd.org/Index.aspx?DataSetCode=BTDIXE_I4

where $\widehat{X} = \begin{pmatrix} \widehat{X}^{11} & 0 & \cdots & 0 \\ 0 & \widehat{X}^{22} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & \widehat{X}^{MM} \end{pmatrix}$, $\widehat{Y} = \begin{pmatrix} \widehat{Y}^{11} & \widehat{Y}^{12} & \cdots & \widehat{Y}^{1M} \\ \widehat{Y}^{21} & \widehat{Y}^{22} & \cdots & \widehat{Y}^{2M} \\ \vdots & \vdots & \ddots & \vdots \\ \widehat{Y}^{M1} & \widehat{Y}^{M2} & \cdots & \widehat{Y}^{MM} \end{pmatrix}$ are MN $\times$ MN matrices that denote the gross output and final demand of each country, respectively, A is the MN $\times$ MN direct input coefficient matrix, and $B = (I - A)^{-1}$ is the MN $\times$ MN Leontief inverse matrix.

Then, we decompose final demand into value added terms (Wang et al., 2022). Based on whether the value added is embodied in domestic final demand $\widehat{Y}^D$, final good exports that directly meet foreign final demand $\widehat{Y}^E$, or intermediate good exports that are input in global production networks ($A^E B$) and ultimately meet global final demand $\widehat{Y}$, the production activities of final demand can be decomposed into pure domestic activities, traditional trade and GVC activities, respectively[3]:

$$\widehat{V}B\widehat{Y} = \widehat{V}L\widehat{Y}^D + \widehat{V}L\widehat{Y}^E + \widehat{V}LA^E B\widehat{Y} = \widehat{V}L\widehat{Y}^D + \widehat{V}L\widehat{Y}^E + \widehat{V}LH\widehat{Y} \tag{3}$$

where $A^D = \begin{pmatrix} A^{11} & 0 & \cdots & 0 \\ 0 & A^{22} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & A^{MM} \end{pmatrix}$ is the domestic direct input coefficient matrix, $A^E = A - A^D$ is the foreign direct input coefficient matrix, $\widehat{V}$ denotes the diagonal direct value added coefficient matrix, $\widehat{Y}^D = \begin{pmatrix} \widehat{Y}^{11} & 0 & \cdots & 0 \\ 0 & \widehat{Y}^{22} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & \widehat{Y}^{MM} \end{pmatrix}$, $\widehat{Y}^F = \widehat{Y} - \widehat{Y}^D$ represents the diagonal domestic and foreign final demand matrix, $L = (I - A^D)^{-1}$ is the domestic Leontief inverse matrix, and $H = A^E B$ is the global industry linkage matrix.

We aim to trace the value added flows of a country s that are induced by foreign final demand, and two parts of the decomposition, $\widehat{V}L\widehat{Y}^E$ and $\widehat{V}LH\widehat{Y}$ in Eq. (3), are considered. The value added imports and exports of country s related to traditional trade activities and GVC activities can be written as follows:

$$VAM^s\_T = \sum_{r \neq s}^{G} V^r L^{rr} Y^{rs} \tag{4}$$

$$VAX^s\_T = \sum_{r \neq s}^{G} V^s L^{ss} Y^{sr} \tag{5}$$

$$VAM^s\_G = \sum_{t,r \neq s}^{G} V^r L^{rr} H^{rt} Y^{ts} \tag{6}$$

$$VAX^s\_G = \sum_{r,t \neq s}^{G} V^s L^{ss} H^{sr} Y^{rt} \tag{7}$$

Subscripts T and G signify traditional trade and GVC activities, respectively. VAM^s_T and VAM^s_G represent the value added imports of country s related to traditional trade and GVC activities. VAX^s_T and VAX^s_G are the value added exports of country s related to traditional trade and GVC activities. VAM^s_T or VAM^s_G implies that upstream countries input the value added for the production of final goods or intermediate goods that are imported directly or indirectly to meet the final consumption of country s. VAX^s_T or VAX^s_G implies that country s inputs the value added for the production of final goods or intermediate goods that are exported to meet the foreign final consumption directly or indirectly.[4]

[3] In the globalized economy, final trade cannot be equivalent to the Ricardian "traditional trade" because it is very likely that foreign intermediate input is used for the productions of final goods. Nonetheless, we can decompose the portion of value added with the same feature of Ricardian "traditional trade". That is, the value added embodied in final products and crossing borders only once for final consumption is related to traditional trade. In GVCs, countries undertake different production tasks based on their comparative advantages and induce the rise in intermediate trade. The value added embodied in intermediate goods and crossing borders at least once is related to GVC activities.

[4] The decomposition is based on forward linkages. Here, we supplement the explanation of value added flows based on backward linkages. Imports of final goods and intermediate goods are composed by value added from across the world. Along numerous value chains of final goods, we can trace the value added imports related to traditional trade and that related to GVC activities. When a country imports intermediate inputs for production to meet final consumption, we can trace the value added imports related to GVC activities.

Define $F = \left(F^1 \quad F^2 \quad \ldots \quad F^M\right)$ as CO_2 emission coefficient matrix, and define $F^s = \left(F_1^s \quad F_2^s \quad \ldots \quad F_N^s\right)$ as CO_2 emission coefficient of N sectors of country s, where $F_j^s = e_j^s / x_j^s$ and e_j^s, and x_j^s are the CO_2 emissions and gross output of sector j in country s, respectively. The CO_2 emissions embodied in final goods can be decomposed into different types of production activities:

$$\widehat{F}B\widehat{Y} = \widehat{F}L\widehat{Y}^D + \widehat{F}L\widehat{Y}^E + \widehat{F}LH\widehat{Y} \tag{8}$$

We focus on the embodied emission flows related to traditional trade and GVC activities in the same way as value added flows. We derive EEM^s_T and EEM^s_G, which indicate the embodied emission imports of country s related to traditional trade and GVC activities, respectively, and EEX^s_T and EEX^s_G, which express the embodied emission exports of country s related to traditional trade and GVC activities.

We further establish the indices of VPM and VPX to evaluate the comprehensive trade benefits of the economy and the environment. The VPM and VPX of country s can be defined as follows:

$$VPM^s = \frac{VAM^s}{EEM^s} \tag{9}$$

$$VPX^s = \frac{VAX^s}{EEX^s} \tag{10}$$

At the production activity level, we can define the VPM and VPX of traditional trade and GVC activities.

The VPM of a country indicates the amount of value added that the country should pay when transferring one unit of carbon emissions through imports, whereas the VPX of a country indicates the amount of value added that the country could gain when undertaking one unit of carbon emissions transferred through exports. Thus, a higher VPX and a lower VPM mean that the comprehensive benefits of exports and imports are promoted.

3.2. Multiplicative SDA modeling of VPM and VPX

We adopt the multiplicative decomposition method to analyze the effects of driving factors on the changes in VPM and VPX and to find ways to narrow the gap between them. We do so due to the ratio form of the indices (Su and Ang, 2015). The approaches to calculate the driving factor effects on changes in the indices include the D&L (Dietzenbacher and Los, 1998; Su and Ang, 2017) and LMDI approaches (Ang, 2015). In this paper, we use the latter, specifically the LMDI-I approach, which has a concise and consistent form for each factor effect (Su and Ang, 2012; Zhao et al., 2017) and because through this approach, it is convenient to aggregate the factor effects by subgroups to analyze their contributions to the overall changes.

Take the decomposition of change in the VPX of traditional trade as an example. The change in VPX^s_T from time 0 to time 1 can be rewritten as the ratio of the change in value added exports related to traditional trade (VAX^s_T) to the change in embodied emission exports related to the traditional trade (EEX^s_T) of country s:

$$D_{VPX^s\_T} = \frac{VPX^{s,1}\_T}{VPX^{s,0}\_T} = \frac{VAX^{s,1}\_T / VAX^{s,0}\_T}{EEX^{s,1}\_T / EEX^{s,0}\_T} = \frac{D_{VAX^s\_T}}{D_{EEX^s\_T}} \tag{11}$$

Then, we decompose the numerator and denominator of Eq. (11) separately. According to Eq. (5), the numerator of Eq. (11), $D_{VAX^s\_T}$, can be decomposed into three driving factor effects:

$$D_{VAX^s\_T} = D_{VAX^s_{Vd}\_T} \bullet D_{VAX^s_{Ld}\_T} \bullet D_{VAX^s_{\_Ye}\_T} \tag{12}$$

where $D_{VAX^s_{Vd}\_T}$ is the domestic value added coefficient effect, $D_{VAX^s_{Ld}\_T}$ is the domestic industrial linkage effect and $D_{VAX^s_{Ye}\_T}$ is the foreign final demand effect. The formulas of the driving factor effects are shown in Appendix A.

$D_{EEX^s\_T}$, the denominator, can also be decomposed into the domestic emission coefficient effect $D_{EEX^s_{Fd}\_T}$, the domestic industrial linkage effect $D_{EEX^s_{Ld}\_T}$, and the foreign final demand effect $D_{EEX^s_{Ye}\_T}$. Thus, the change in VPX^s_T can be decomposed into four driving factor effects:

$$D_{VPX^s\_T} = \frac{D_{VAX^s_{Vd}\_T} \bullet D_{VAX^s_{Ld}\_T} \bullet D_{VAX^s_{Ye}\_T}}{D_{EEX^s_{Fd}\_T} \bullet D_{EEX^s_{Ld}\_T} \bullet D_{EEX^s_{Ye}\_T}}$$

Table 1
Annotation of the driving factor effects on the changes in VPM and VPX.

Abbreviations	Definitions	Abbreviations	Definitions
D_{VPI}	Change in VPM	D_{VPX}	Change in VPX
D_{Ve}	Foreign value added coefficient effect	D_{Vd}	Domestic value added coefficient effect
D_{Fe}	Foreign emission coefficient effect	D_{Fd}	Domestic emission coefficient effect
D_{Le}	Foreign industrial linkage effect	D_{Ld}	Domestic industrial linkage effect
D_H	Global industrial linkage effect	D_H	Global industrial linkage effect
D_{Yd}	Domestic final demand effect	D_{Ye}	Foreign final demand effect

$$= D_{VAX^s_{Vd}\_T} \bullet \frac{1}{D_{EEX^s_{Fd}\_T}} \bullet \frac{D_{VAX^s_{Ld}\_T}}{D_{EEX^s_{Ld}\_T}} \bullet \frac{D_{VAX^s_{Ye}\_T}}{D_{EEX^s_{Ye}\_T}}$$

$$= D_{Vd\_T} \bullet D_{Fd\_T} \bullet D_{Ld\_T} \bullet D_{Ye\_T} \quad (13)$$

where D_{Vd_T}, D_{Fd_T}, D_{Ld_T}, and D_{Ye_T} are the domestic value added coefficient effect, domestic emission coefficient effect, domestic industrial linkage effect and foreign final demand effect that contribute to the change in VPX^s_T, respectively.

In Appendix A, we show more details about the decomposition of the changes in the VPX and the VPM of traditional trade and GVC and how to derive the decomposition of changes in the aggregate VPM and VPX from those at the production activity levels. The driving factor effects on the changes in aggregate VPM and VPX are shown in Table 1.

3.3. Data sources and processing

The World Input-Output Tables (WIOTs) from 2000 to 2014 used in this paper are from the World Input-Output Database (WIOD), and the CO_2 emission data during this period are from the EU Science Hub. The tables contain the IO data of 43 countries and the rest of the world with 56 sectors, which are integrated into 22 in this paper (Appendix B).

The data processing of this paper involves two aspects. First, we changed the data at current prices to constant prices in 2010 so that VPM and VPX could be compared effectively, following the instructions of Los, Gouma, Timmer, and IJtsma (2014). The exchange rate and the price deflators of gross output, intermediate inputs and gross value added all came from the WIOD's socioeconomic accounts. Other price deflators were calculated based on data from the UN National Accounts and Taiwanese National Accounts. Second, this paper addressed the zero and negative elements in the WIOTs following the method of Ang et al. (Ang and Liu, 2007a, 2007b), which makes the LMDI method robust to zero and negative values (Su and Ang, 2012).

4. Results

4.1. Dual effects of China's international trade

After acceding to the WTO in 2001, China's international trade witnessed rapid development. The accompanying dual effects of the economy and the environment have been increasing simultaneously.

For a country, imports of final or intermediate goods are accompanied not only by transferring production to upstream countries but also by carbon emission transfer and value added payoff. In contrast, exports of final or intermediate goods are accompanied by value added exports and embodied emission exports, which indicates that the country undertakes the carbon emission transferred from downstream countries while gaining value added from exports in return. Moreover, most of the production tasks undertaken by China have long been characterized by low value added and high carbon emission intensity. Thus, it is necessary to distinguish between

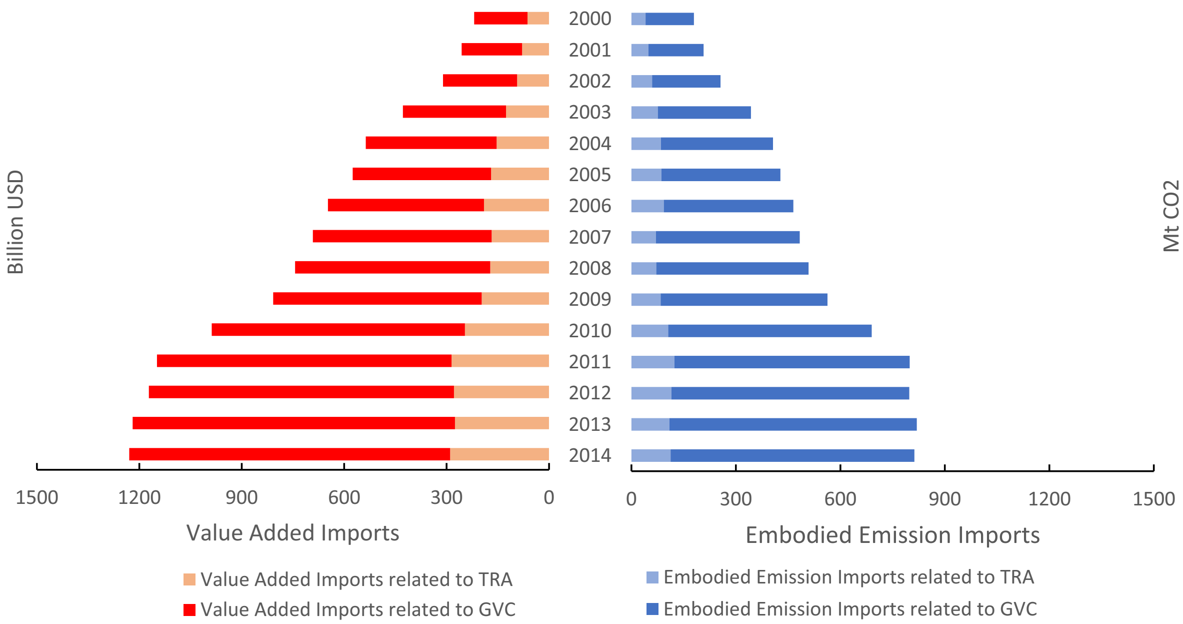

Fig. 1. Value added imports and embodied emission imports of China by production activity.
Note: TRA denotes traditional trade activities, and GVC denotes GVC activities. The same is true in Fig. 2 below.

traditional trade activities and GVC activities, with the former related to traded final goods and the latter related to traded intermediate goods.

At the aggregate level, the economic and environmental effects of imports continue to increase. The increasing trends can largely be attributed to the growing share of value added imports related to GVC activities, which indicates an increasing dependence on foreign intermediate inputs that are used directly and indirectly for production to meet domestic final demand in China. In Fig. 1, the value added paid by China and carbon emissions transferred to upstream countries increased simultaneously. The value added paid by China increased from 219.3 billion USD in 2000 to 1229.5 billion USD in 2014, and the carbon emissions transferred to upstream countries increased from 179.3 Mt. in 2000 to 812.6 Mt. in 2014. During this period, the value added imports and embodied emission imports related to GVC grew by average annual rates of 14.12% and 12.68% respectively. These figures were higher than those related to traditional trade, with the average annual growth rates being 12.17% and 8.50%.

As illustrated in Fig. 2, the value added exports and embodied emission exports driven by the final demand of downstream countries show increasing trends as well. Value added exports increased from 350.5 billion USD in 2000 to 1787.2 billion USD in 2014, and embodied emission exports increased from 612.2 Mt. in 2000 to 2484.4 Mt. in 2014. In contrast to imports, the value added exports and embodied emission exports related to both traditional trade and GVC make essential contributions to the increasing trend of the dual effects of China's exports.

In Figs. 1 and 2, we can find obvious imbalances in the value added and embodied emission flows between imports and exports. That is, China tends to gain lower value added when undertaking one unit of carbon transfer in exports and pay higher value added when transferring one unit in imports. Regarding production activities, the value added and embodied emission imports related to GVC activities accounted for more than 75% in 2014, while the exports related to traditional trade and GVC took approximately equal shares, with lower embodied value added and higher embodied emissions in exports related to GVC activities than traditional trade. This indicates that China's production tasks in the GVC division are still locked into the low value-added activities of GVCs with high carbon emission intensity.

As shown in the pie charts in Fig. 3, China's imports from developed economies were much more environmentally friendly and demanded higher value added than its imports from developing economies, which is consistent with the result of Zhang et al. (2019). The share of value added imports from developed economies was 55.35%, while the share of embodied emission imports from them was only 35.50%. Among 22 sectors, a large proportion of China's value added imports from Electrical and Optical Equipment (EOE), Machinery, Nec (MACN), Transport Equipment (TRE), Wholesale and Retail (WRE), Knowledge-Intensive Business Services (KIBS) was from developed economies, with very low carbon being transferred to them. Most of the value added imports from Electrical and Optical Equipment (EOE), Wholesale and retail (WRE) and Knowledge-Intensive Business Services were related to GVC activities, and most from Machinery, Nec (MACN) and Traditional Trade Equipment (TRE) were related to traditional trade. In contrast, a large proportion of China's embodied emission imports from Electricity, Gas and Water Supply (EGW), Mining (MIN), Manufacturing, Nec, Recycling (MNR), and Rubber and Plastics (RUB) were mainly from developing economies and related to GVC activities predominantly.

The pie charts in Fig. 4 show that the share of China's exports to developed economies was slightly higher than its share of exports to developing economies. Embodied emission exports of Electricity, Gas and Water Supply (EGW), Basic Metals and Fabricated Metal (BAS), Other Non–Metallic (ONM), and Chemicals (CHE) were the highest, from which insufficient value added was gained. In contrast, China benefited the most from exports of final and intermediate goods and services from Knowledge-Intensive Business Services (KIBS), Wholesale and Retail (WRE), and Electrical and Optical Equipment (EOE), which caused few carbon emissions as well.

4.2. *Value added per embodied emission in the imports and exports of China*

Based on the fact that the dual effects of China's foreign trade continued increasing and there was an imbalance between imports and exports, we establish the VPM and VPX indices to analyze the change trends and the relative magnitudes of the dual effects at the aggregate, production activity, bilateral and sectoral levels.

The VPM of China increased significantly from 2000 to 2014, and the VPM was much higher for traditional trade than for GVC (Fig. 5). The VPM of traditional trade increased by 65.96%, while it increased by only 19.19% for GVC activities. In 2014, the VPM of traditional trade was 2.58 USD/Mt. CO_2, nearly twice the VPM of GVC activities, which was 1.34 USD/Mt. CO_2. This result was due to the difference in the structures of final and intermediate imports induced by China's final demand. In Fig. 3, intermediate imports accounted for a larger share of value added from the energy-intensive sector Electricity, Gas and Water Supply (EGW), and dirty manufacturing sectors such as Transport and Postal (TWP), Basic Metals and Fabricated Metal (BAS), and Chemicals (CHE). In contrast, final imports accounted for a larger share of value added from manufacturing and service sectors such as Electrical and Optical Equipment (EOE), Machinery, Nec (MACN), Knowledge-Intensive Business Services (KIBS), and Wholesale and retail (WRE).

The VPX of China has shown an increasing trend since 2005, but it was significantly lower than VPM (Figs. 5 and 6). The VPX of traditional trade increased by 40.40%, and the VPX of GVC increased by only 12.94%, which were favorable changes in exports for China. However, there was a large gap between VPX and VPM, which reflects the imbalance in the value added and embodied emission flows between imports and exports, as illustrated in Section 3.1. For example, in 2014, the aggregate VPM was 1.51 billion USD/Mt. CO_2, more than twice the aggregate VPX, which was only 0.72 billion USD/Mt. CO_2. These results indicate that China's level of ability to gain value added and reduce carbon emissions from production lags far behind the overall level of its import trade partners.

From the perspective of production activities and economic groups, we find that the large gap between aggregate VPM and VPX is mainly because of the fact that developed economies gained much higher value added per embodied emission than China gained through exports in GVC activities. As shown in Fig. 7, there was a large gap between the VPM and VPX of traditional trade and GVC

Fig. 2. Value added exports and embodied emission exports of China by production activity.

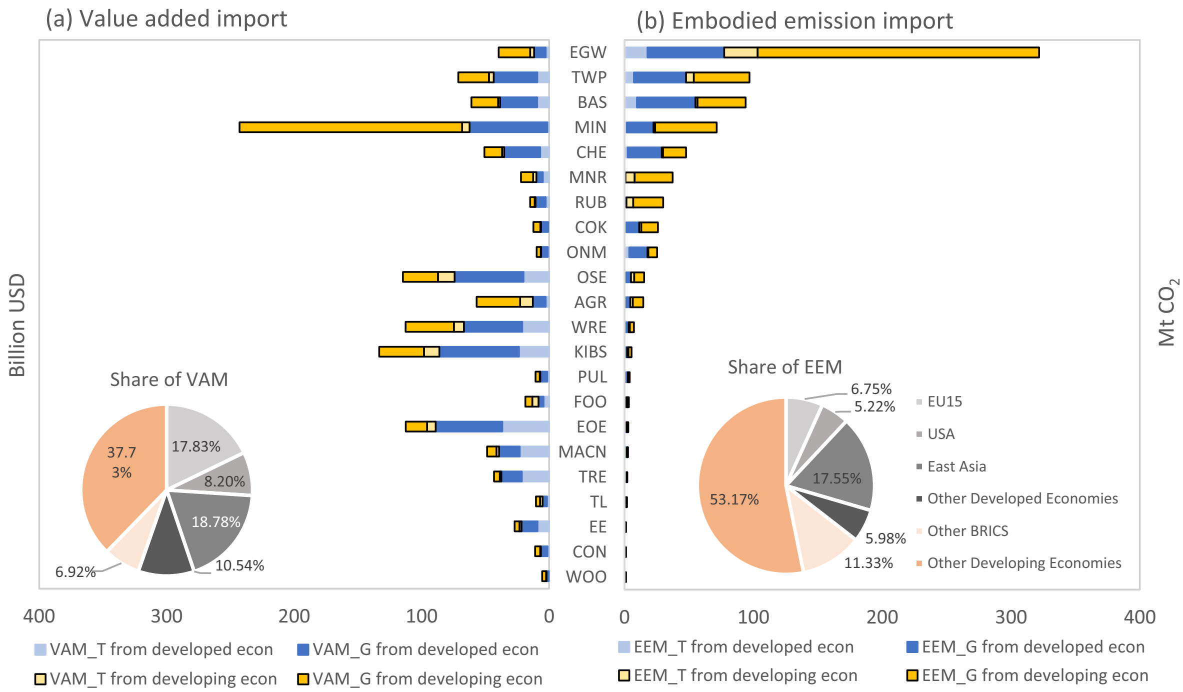

Fig. 3. Value added imports and embodied emission imports of China by sectors and bilateral partners, 2014.
Note: *VAM_T* and *VAM_G* denote China's value-added imports related to traditional trade and GVC activities, respectively. *EEM_T* and *EEM_G* denote China's embodied emission imports related to traditional trade and GVC activities, respectively.

activities under the bilateral trade between China and developed economies. In the above analysis, imports related to GVC accounted for a much larger weight (Fig. 1), and exports related to GVC accounted for almost half (Fig. 2). Additionally, the VPX of GVC was even lower than the VPX of traditional trade due to the production tasks involving mostly low technology undertaken by China. Therefore, the large gap is mainly due to the value added trade between China and developed economies for GVC activities.

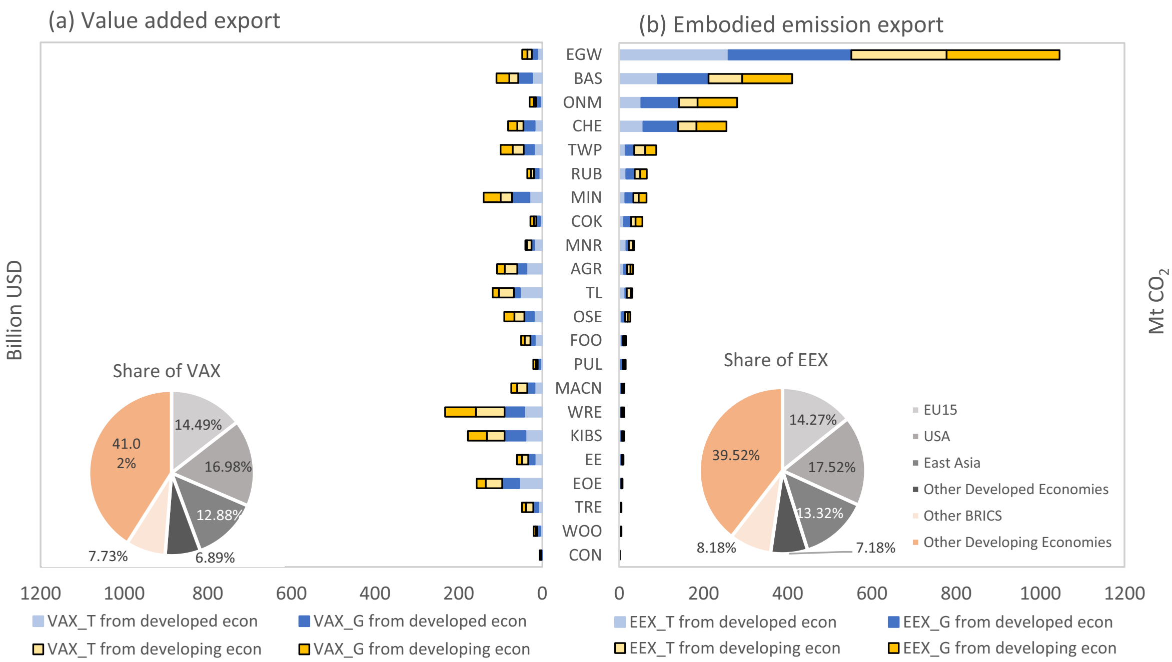

Fig. 4. Value added exports and embodied emission exports of China by sectors and bilateral partners, 2014.
Note: *VAX_T* and *VAX_G* denote China's value added exports related to traditional trade and GVC activities, respectively. *EEX_T* and *EEX_G* denote China's embodied emission exports related to traditional trade and GVC activities, respectively.

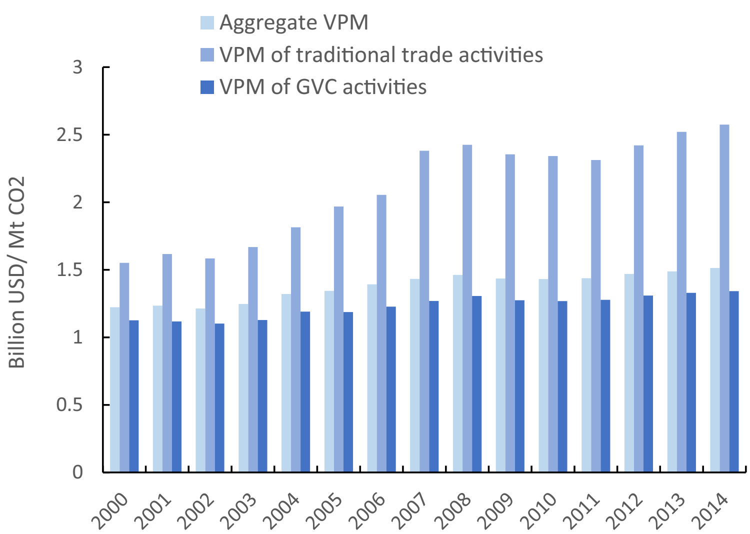

Fig. 5. Value added per embodied emission in the imports of China at the aggregate and production activity levels.

We next compare China's VPX with its VPM under bilateral trade with other economies at the bilateral-sector level (Table 2). Since the indices are calculated based on forward linkages or from a production perspective rather than based on backward linkages or from a final good perspective, the comparison is in regard to the value added gained by a sector in an economy when undertaking one unit of carbon emission transfer. Thus, it is noteworthy that (1) the indices of traditional trade and GVC at the sectoral level are equal under the homogeneity assumption of the IO model. (2) We provide the bilateral-sectoral VPMs in the first six columns but only bilateral VPXs in the last column because the bilateral-sectoral VPXs of China are calculated from the production perspective and are irrelevant to the destinations of value added exports.

For most of the manufacturing sectors and service sectors, the VPMs under bilateral trade between China and developed economies were much higher than the VPXs. For example, when transferring one unit of carbon emissions through China's imports, much higher

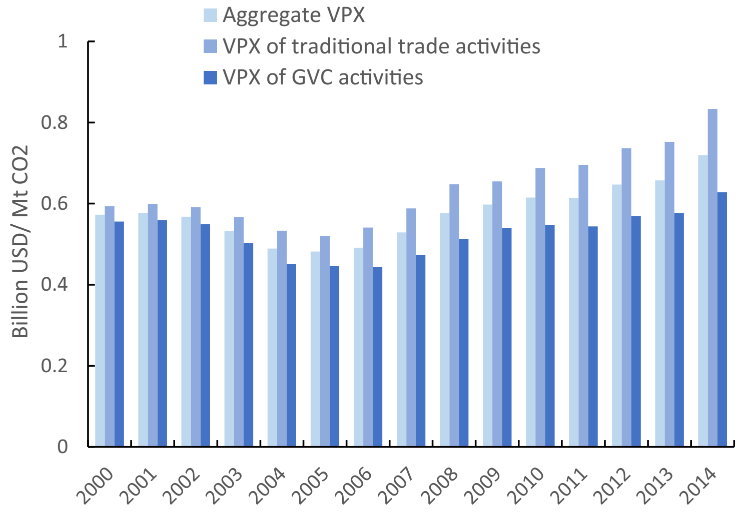

Fig. 6. Value added per embodied emission in the exports of China at the aggregate and production activity levels.

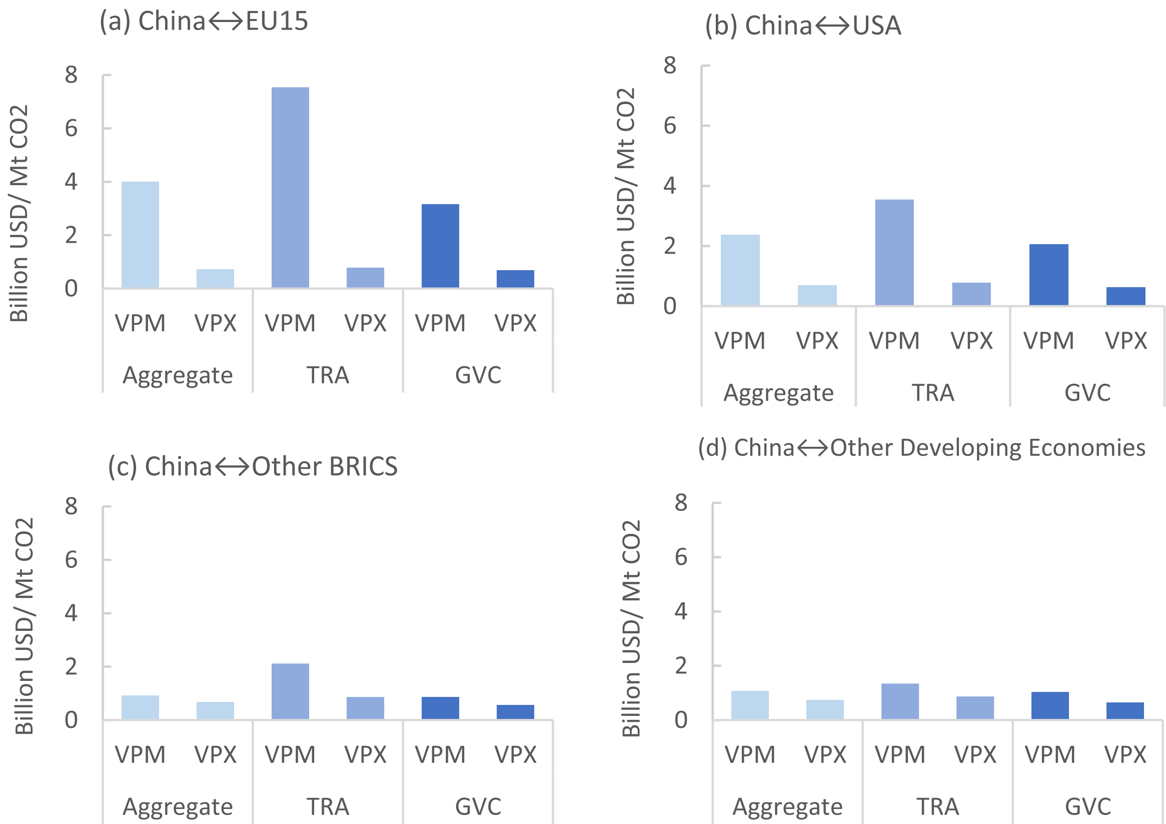

Fig. 7. VPM and VPX between China and its trade partners at the aggregate and production activity levels.

value added was induced by Electrical and Optical Equipment (EOE), Electrical Equipment (EE), Transport Equipment (TRE), and Knowledge-Intensive Business Services (KIBS) in developed economies, such as Western Europe, the USA, and East Asia. However, these sectors in China have had less ability to gain value added and reduce carbon emissions when exporting. These bilateral-sectoral VPMs are also more essential due to the higher shares in imports (Fig. 3), and thus, they have a higher weight of aggregate VPM. In contrast, under bilateral trade with developing economies, many of China's sectoral VPXs were found to be higher than the VPMs. For

Table 2
Comparison of VPM and VPX at the bilateral-sectoral level in 2014.

	VPM						VPX
	Developed economies				Developing economies		
	EU15	USA	East Asia	Other developed economies	Other BRICS	Other developing economies	
AGR	2.70	2.94	4.87	2.58	3.18	4.99	3.29
MIN	2.40	3.30	0.10	5.18	1.28	4.89	2.17
FOO	6.39	3.65	8.84	6.65	6.40	5.41	3.17
TL	9.60	5.85	4.65	8.09	4.23	5.82	3.81
WOO	7.27	3.78	7.18	3.60	1.93	7.63	4.24
PUL	2.85	1.97	3.20	2.90	2.30	2.64	1.41
COK	0.21	0.95	0.59	0.55	0.58	0.38	0.52
CHE	2.27	1.67	0.85	1.27	0.47	0.95	0.32
RUB	11.29	2.30	10.06	7.60	5.21	0.13	0.55
ONM	0.52	0.37	0.29	0.52	0.16	0.62	0.11
BAS	1.25	1.22	0.51	0.58	0.18	1.00	0.27
EOE	57.86	56.77	52.98	54.88	6.38	19.12	20.63
EE	33.63	12.22	35.30	26.26	6.74	13.03	6.09
MACN	32.18	5.84	29.38	25.71	5.80	13.81	6.19
TRE	24.97	13.73	26.62	24.35	6.04	18.90	9.63
MNR	28.38	10.85	7.65	26.96	10.86	0.31	1.15
EGW	0.31	0.12	0.11	0.16	0.07	0.12	0.05
CON	14.00	9.17	19.29	22.89	9.61	6.45	7.78
WRE	25.18	32.31	15.91	19.82	19.37	9.78	19.45
TWP	1.21	0.58	0.91	1.10	0.80	0.52	1.14
KIBS	75.66	29.03	26.98	43.13	29.19	12.66	15.41
OSE	25.66	13.90	8.04	15.24	11.79	3.34	3.49

example, Agriculture (AGR), Basic Metals and Fabricated Metal (BAS), and Electrical and Optical Equipment (EOE) in China had a higher VPX than VPM under bilateral trade with other BRICS countries.

4.3. Discussion of the multiplicative SDA of VPM and VPX

The fact that China's VPM was much higher than its VPX emphasizes the importance of studying how to narrow the gap between them. In this section, we reveal the total and bilateral-sectoral contributions of driving factors to the increase in VPM and VPX at the aggregate and production activity levels.

As shown in Fig. 8, China's aggregate VPM increased slightly by 8.16% during the 2007–2014 period (Fig. 8b), although it experienced a sharp increase of 20.02% from 2000 to 2007 (Fig. 8a). The emission coefficient of upstream economies was the most significant factor during the 2000–2007 period, contributing 114.82% to the increase in VPM.[5] During the 2007–2014 period, all driving factors except for the foreign value-added coefficient contributed positively to the increase in China's VPM. However, the contribution of the emission coefficient of upstream economies was not as significant as that of the previous period, which was 27.77%.

In contrast, China's VPX showed different change trends during the two periods. From 2000 to 2007, the aggregate VPX decreased by 7.62%. The main reasons were weakening domestic industry linkages and deepening integration into GVCs, whose contribution to the negative increase were 230.15% and 166.03%, respectively. In contrast, the contribution of the carbon emission coefficient effect was −322.68%, implying a sharp decrease in carbon emission intensity in China. During the 2007–2014 period, the aggregate VPX increased dramatically by 34.52%. The decreased carbon intensity of China significantly contributed 58.99% to the increase in VPX. In addition, the domestic industry linkage effect became positive, but global industry linkage effect was still negative; their contributions were 50.90% and −13.61%, respectively. The domestic value added coefficient effect contributed much less (1.90%) to the increase in the aggregate VPX.

Domestic final demand, the factor that is the most correlated to China, positively contributed to the increase in the VPMs of traditional trade and GVC activities in both periods. As opposed to the 2000–2007 period, the contribution of the domestic final demand effect to the increase in the VPM of GVC activities became much larger than that of traditional trade (46.76% and 14.53%, respectively) during the 2007–2014 period. This result implies that the foreign intermediate good exports of high value added and low carbon emission intensity absorbed by China for production to meet domestic final consumption have shown a more significant increasing trend than the foreign final good counterparts to China.

During the 2007–2014 period, both the domestic emission coefficient effect and the domestic industry linkage effect on the increase in the VPX of traditional trade were higher than those on the increase in the VPX of GVC activities. These results indicate that the decrease in carbon emission intensity and the strengthening of domestic industry linkages will improve the VPX of traditional trade more effectively. Decreasing to the absolute value, global industry linkage effect was still negative during this period. There is still much room to improve the VPX of GVC activities by undertaking more production sharing activities involving higher technology and

[5] The contribution is the ratio of the log of the driving factor effect to the log of the total effect.

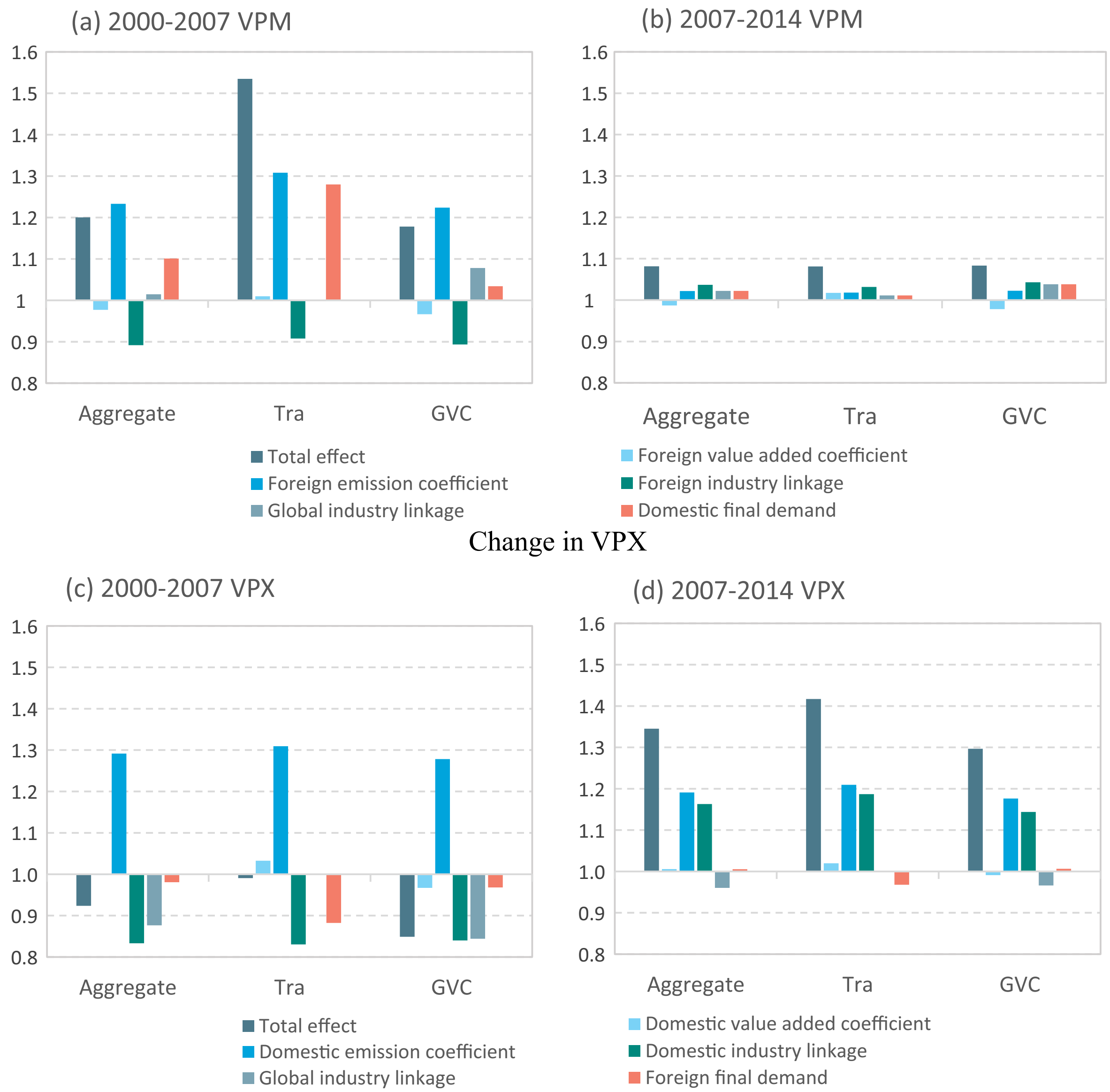

Fig. 8. Changes in the VPM and VPX of China, 2000–2007 and 2007–2014.
Note: Aggregate denotes changes in *VPM* and *VPX* at the aggregate level, and *Tra* and *GVC* denote changes in the indices of traditional trade activities and GVC activities, respectively.

upgrading China's GVC position. This is because that China undertakes part of processing trade tasks in GVC activities that is not carbon intensive, while traditional trade activities are more sensitive to changes in domestic emission coefficient and require supply chain collaboration to a larger extent. Additionally, foreign final demand had a negative effect on the increase in the VPX of traditional trade in both periods. This result implies that more domestic intermediate inputs of low value added and high carbon emission intensity were embodied in China's final good exports. However, during the 2007–2014 period, the foreign final demand effect on the VPX of GVC activities became positive, indicating that the structure of China's intermediate good exports became more environmentally friendly.

Before analyzing bilateral-sectoral contributions that will provide more tailored policy implications of ways to decrease the high dependency in imports and enhance sustainability and profitability in exports, the following investigation of how China's bilateral trade and driving factors contribute to the increases in VPM and VPX at the aggregate and production activity levels will serve as a foundation.

At the aggregate level, Tables 3 and 4 show that China's bilateral trade with developed economies contributed greatly to the increase in VPM (201.43%) but contributed far less to the increase in VPX (55.41%). China's final demand effect was the main driving factor of the increase in VPM, with a contribution of 152.87%. This implies that China has imported more goods and services of high

Table 3
Bilateral contributions of changes and the driving factors to VPM in China, 2007–2014 (unit: %).

Bilateral trade	Changes and driving factors					
	Total effect	Foreign value-added coefficient	Foreign emission coefficient	Foreign industry linkage	Global industry linkage	Domestic final demand
Aggregate VPM						
Developed economies	201.43	12.67	52.25	−29.10	12.74	152.87
Developing economies	−101.43	−29.17	−24.48	75.18	1.76	−124.72
VPM of traditional trade						
Developed economies	217.33	30.18	62.44	−26.33	0.00	151.04
Developing economies	−117.33	−8.04	−39.30	66.52	0.00	−136.51
VPM of GVC						
Developed economies	175.54	7.29	50.06	−25.12	0.53	142.78
Developing economies	−75.54	−34.83	−22.27	77.82	−0.25	−96.02

Table 4
Bilateral contributions of changes and the driving factors to VPX in China, 2007–2014 (unit: %).

Bilateral trade	Changes and driven factors					
	Total effect	Domestic value-added coefficient	Domestic emission coefficient	Domestic industry linkage	Global industry linkage	Foreign final demand
Aggregate VPX						
Developed economies	55.41	1.57	33.98	27.94	−7.57	−0.50
Developing economies	44.59	0.33	25.01	22.96	−6.04	2.33
VPX of traditional trade						
Developed economies	52.17	3.64	31.22	26.11	0.00	−8.81
Developing economies	47.83	1.94	23.35	23.08	0.00	−0.53
VPX of GVC						
Developed economies	59.65	−1.49	36.28	29.49	−6.99	2.35
Developing economies	40.35	−1.96	26.30	22.25	−6.30	0.07

value added and low carbon intensity from developed economies. The domestic emission coefficient and domestic industry linkages were the main driving factors of the increase in VPX, with contributions of 33.98% and 27.94%, respectively.

In contrast, China's bilateral trade with developing economies contributed to the decrease in VPM and the increase in VPX, whose favorable contributions were −101.43% and 44.59%, respectively. The main driving factor of the decrease in VPM was China's final demand, and that of the increase in VPX was China's emission coefficient and industry linkages; their contributions were −124.72%, 25.01% and 22.96%, respectively. This implies that China has imported more goods of high carbon intensity from developing economies. It is necessary for China to strengthen green technology cooperation with developing economies to decrease the carbon transfer.

Although VPM presented slight growth during the 2007–2014 period, China's bilateral trade with developed and developing economies experienced polarized changes, with its contributions to the increase in VPM being 201.43% and −101.43%, respectively. In other words, China's bilateral trade contributed to improving its comprehensive economic and environmental benefits in opposite directions. The main reason was the opposite contribution of the domestic final demand effect, indicating a totally different change trends in the demand structures of China's imports from developed and developing economies.

When decomposing by production activity, the domestic final demand effect on the increase in the VPM of traditional trade and

GVC was also polarized. Additionally, the foreign final demand effect on the change in the VPX of traditional trade and the global industry linkage effect on the change in the VPX of GVC were significantly negative, with contributions of −9.34% and −13.29%, respectively. It will be interesting to further explore the bilateral-sectoral contributions of these driving factors that boosted VPM or prevented VPX from improving.

Fig. 9a shows the bilateral-sectoral contributions of domestic final demand effects on backward linkages or from the perspective of products to changes in the VPM of traditional trade. Among 22 sectors in developed economies, the increase in the domestic final demand for their final products of most sectors contributed positively to the increase in the VPM of traditional trade, with Transport Equipment (TRE), Electrical and Optical Equipment (EOE), Wholesale and Retail (WRE) and Chemicals (CHE) having the most significant contribution. In contrast, for imports from developing economies, an increase in the domestic final demand that induces imports of final goods from Electrical and Optical Equipment (EOE), Manufacturing, Nec; Recycling (MNR), Transport and Postal (TWP), and Coke (COK) negatively and substantially contributed to the increase in the VPM of traditional trade.

The final demand of China induced a large number of imports of intermediate inputs that are used for production to meet domestic final demand. In Fig. 9b, the bilateral-sectoral contributions of the domestic final demand effects on the change in the VPM of GVC were not as significant as those on the change in the VPM of traditional trade. The probable reason is that we aggregate the bilateral-sectoral contributions based on backward linkages, including the inputs of both developed and developing economies; therefore, the polarized domestic final demand effects are largely offset. However, notably, the increase in the domestic final demand that induced imports of final goods and intermediate inputs from Transport Equipment (TRE), Food (FOO), and Electrical and Optical Equipment (EOE) in both developed and developing economies significantly contributed to the increase in the VPM of GVC.

Therefore, for final products imported from the Chemicals (CHE) sector in developed economies and intermediate inputs and final goods from the Transport Equipment (TRE) and Electrical and Optical Equipment (EOE) sectors in both developed and developing economies, China should support the domestic layout and development of core supply chains to ensure a complete domestic supply network and construct green supply chains to realize sustainable economic growth. In addition, for final products imported from the Electrical and Optical Equipment (EOE), Manufacturing, Nec, Recycling (MNR), Transport and Postal (TWP), and Coke (COK) sectors in developing economies, China should take advantage of strategic opportunities such as the Green Belt and Road Initiative to export cleaner production technologies to these sectors and the upstream sectors in developing countries to help mitigate global climate change. The reason is that the growing demand for these products significantly contributed to the decrease in VPM and transferred too many carbon emissions to developing economies.

Fig. 9c and d show the bilateral-sectoral contributions of the foreign final demand effect to change in the VPX of traditional trade and that of the global industry linkage effect to change in the VPX of GVC, respectively. We aggregate the effects based on forward linkages as Fig. 8 and Tables 3 and 4 aggregate them, meaning that we take all the direct and indirect domestic sectoral contributions into consideration to investigate how the sectoral development of production and integration into GVCs influenced the comprehensive benefits of exports. In Fig. 9c and d, changes in foreign final demand and deepening integration into GVCs induced more domestic intermediate inputs of relatively low value added and high emission intensity, especially those from Electricity, Gas and Water Supply (EGW), Basic Metals and Fabricated Metal (BAS), Other Non-Metallic (ONM) and Chemicals (CHE). In other words, the domestic intermediate inputs from these sectors significantly contributed to the decrease in the VPX of traditional trade and GVC. Therefore, on the one hand, China is encouraged to apply cleaner energy and conduct R&D in carbon reduction technologies and production technologies in these sectors to decrease their emission intensity and enhance their ability to gain value added. On the other hand, Knowledge-Intensive Business Services (KIBS) could be a source of the increase, as it was the second most significant contributor to the increase in the VPXs of China after only Wholesale and retail (WRE), with the contribution being approximately 10%. China should expand the share of intermediate inputs from KIBS to promote the servicification of manufacturing. Given the different effects of different sources of intermediate inputs from KIBS on enhancing GVC activities (Du and Agbola, 2022), China is encouraged to scale up domestic intermediate inputs from KIBS and undertake more knowledge-intensive production tasks in GVCs to promote an increase in China's GVC position.

5. Conclusion and implications

This paper analyzed the imbalance of the dual economic and environmental effects between China's imports and exports by adopting the WIOTs and CO_2 emission data from 2000 to 2014 collected from the WIOD and EU Science Hub. VPM and VPX at the aggregate, production activity, bilateral and sectoral levels were proposed to analyze the changing trends and the relative magnitudes between the dual effects of China's trade flows. Then, a multiplicative SDA model and the LMDI-I approach were used to decompose the effects of driving factors on changes in VPM and VPX at the aggregate, bilateral and economy-sector levels so that we could investigate how to narrow the large gap between China's VPM and VPX. The main conclusions are as follows:

First, during the 2000–2014 period, the growth in the dual effects of imports was mainly attributed to the growing share of GVC activities and that of exports mainly attributed to both traditional trade activities and GVC activities. However, there was a significant imbalance as a result of which China tended to gain lower value added when undertaking one unit of carbon transfer in exports and pay higher value added when transferring one unit in imports. In 2014, the aggregate VPM was more than twice the aggregate VPX. The large gap was mainly due to the much higher value added per embodied emission gained by developed economies than that of China in GVC activities.

Second, with the increase in the dual effect of China's imports, China needed to pay a large amount of value added for carbon transfer due to its dependence on intermediate inputs and final goods from capital- and technology-intensive manufacturing and services in developed economies, such as Electrical and Optical Equipment (EOE), Machinery, Nec (MACN), Transport Equipment

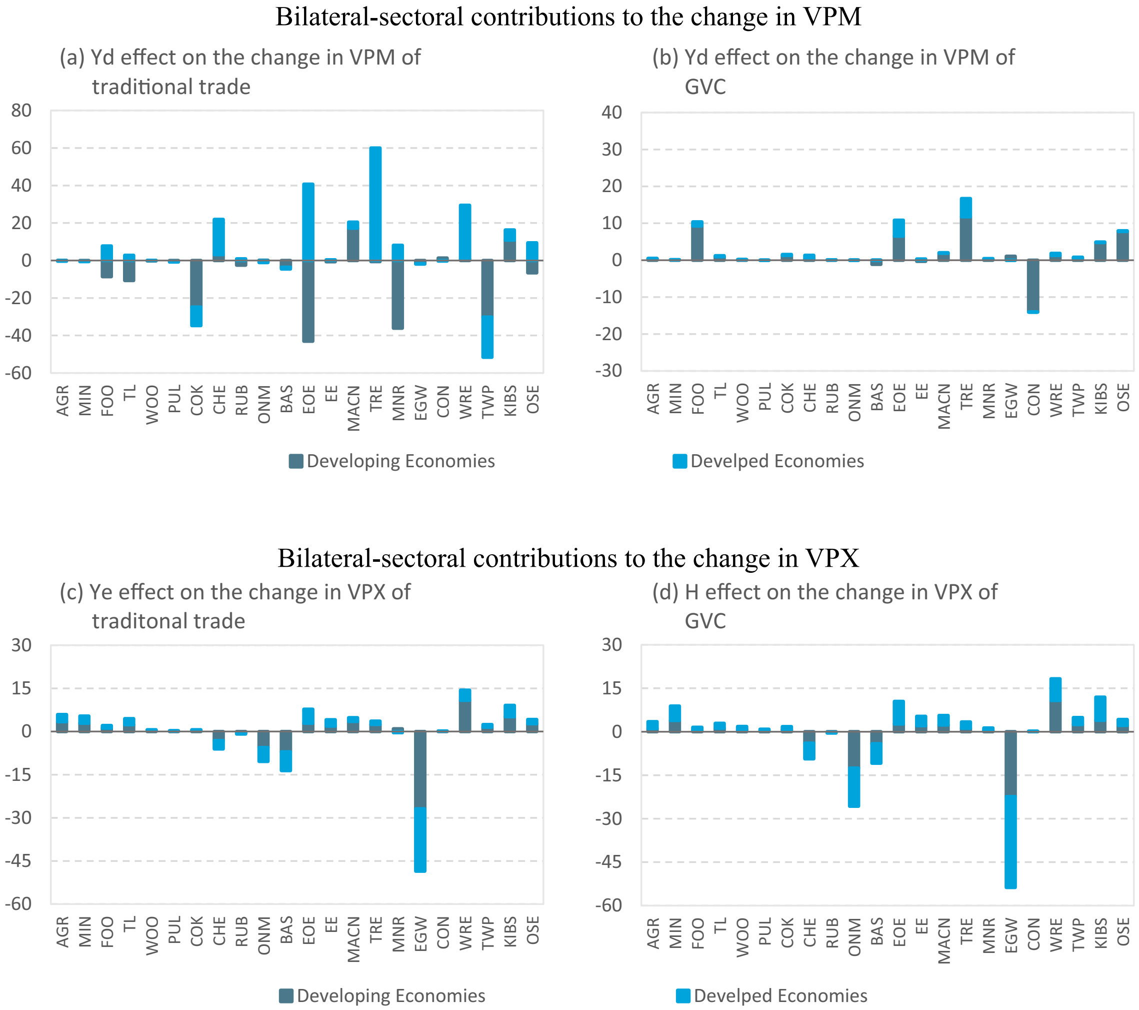

Fig. 9. Bilateral-sectoral contributions of driving factors to changes in VPM and VPX, 2007–2014 (unit: %).
Note: The bilateral-sectoral contributions of driving factors to changes in the *VPM of traditional trade* (a) and *VPM of GVC* (b) are calculated based on backward linkages or from the perspective of the final product, while those to changes in the *VPX of traditional trade* (c) and *VPM of GVC* (d) are calculated based on forward linkages or from the perspective of production.

(TRE), Wholesale and retail (WRE), and Knowledge-Intensive Business Services (KIBS). By contrast, its imports have induced many intermediate inputs from energy supply, primary products and labor-intensive manufacturing, leading to carbon leakage in developing economies and the transfer of excessive carbon emissions to them, such as Electricity, Gas and Water Supply (EGW), Mining (MIN), Manufacturing, Nec; Recycling (MNR), and Rubber and Plastics (RUB). For most manufacturing and service sectors, China's VPMs under bilateral trade with developed economies were much higher than its VPXs. In addition, under bilateral trade with developing economies, many of China's sectoral VPXs were found to be higher than its VPMs.

Third, China's aggregate VPM increased slightly by 8.16% from 2007 to 2014. Domestic final demand effect, the driving factor effect that is the most correlated to China, positively contributed to the increase in the VPMs of traditional trade and GVC activities, with the contribution being much larger to the latter. This result implies that the foreign intermediate good exports of high value added and low carbon emission intensity absorbed by China for production to meet its final consumption have shown a more significant increasing trend. In addition, we found polarized domestic final demand effects under China's bilateral trade with developed and developing economies, with contributions of 152.87% and − 124.72%, respectively, which drove China's bilateral trade to make polarized contributions to the increase in VPM.

Fourth, the aggregate VPX increased dramatically by 34.52% during the 2007–2014 period. The main drivers of the dramatic increase were the domestic emission coefficient effect and domestic industry linkage effect, whose contributions were 58.99% and 50.90%, respectively. Both driving factors boosted the increase in the VPX of traditional trade and GVC activities, with higher effects on the former. In contrast, the contribution of the global industry linkage effect was −13.28%. There is still much room to improve the VPX of GVC activities by undertaking more production sharing activities involving higher value added and lower carbon emission intensity.

The SDA reveals the influences of driving factors on changes in China's VPM and VPM at the aggregate, production activity, bilateral and sectoral levels. The results have significant policy implications for promoting the comprehensive economic and environmental benefits of China's imports and exports.

First, the significant effects of the domestic carbon emission coefficient on the increase in China's VPX demonstrates the importance of reducing carbon emission. China should seize the strategic opportunities to promote green cooperation with developed countries, for example, by jointly establishing carbon markets, promoting cooperation on carbon capture, utilization and storage, and enhancing multilateral collaboration on climate-related domestic policies. It is necessary to realize co-benefits with joint efforts to promote deeper cooperation in existing partnerships, such as the EU-China partnership on climate change and the "China-Japan-ROK + X" Cooperation, through which China can benefit from improving domestic mitigation policies and measures and green technology spillovers. Specifically, the EU-China Joint Statement on Climate Change was issued in 2015 for the purpose of jointly combating global climate change and achieving sustainable economic and social development.[6] The "China-Japan-ROK + X" Cooperation was proposed in 2019 and supported as a new attempt at regional cooperation on sustainable economic growth, environmental protection, sanitation and so on.[7] This cooperation exploits the comparative advantages of the three countries and a fourth country.

Second, the domestic industry linkage effect significantly contributed to the increase in China's VPX, while the contribution of the domestic value added coefficient effect was only 1.90% during the 2007–2014 period. These results are closely related to the improvement in the efficiency and quality of domestic supply chains. On the one hand, China should remove implicit regional barriers to merchandise trade and factor mobility by eliminating local protectionism, establishing a unified and competitive national market and coordinating the roles of the government and the market. Geography regional barriers also hinder efficiency improvement; thus, it is necessary to accelerate the infrastructure construction of transportation and logistics. On the other hand, enterprises should be encouraged to upgrade their production technologies, dirty intermediate inputs should be reduced, and the servicification of manufacturing should be promoted. Additionally, breakthrough advanced technologies, such as artificial intelligence and chip technology, should be supported to improve the quality of domestic supply chains from the supply side and to increase the domestic value added coefficient.

Third, the increase in domestic final demand that induces final products from Transport Equipment (TRE), Electrical and Optical Equipment (EOE), and Chemicals (CHE) in developed economies significantly contributed to the increase in the VPM of traditional trade. The increase in the domestic final demand that induces intermediate inputs and final goods from Transport Equipment (TRE) and Electrical and Optical Equipment (EOE) in developed and developing economies significantly contributed to the increase in the VPM of GVC. Therefore, China should support the domestic layout and development of the core supply chains of these sectors and their upstream enterprises to ensure a complete domestic supply network and construct green supply chains to realize sustainable economic growth. By contrast, an increase in domestic final demand that induces final products from Electrical and Optical Equipment (EOE), Manufacturing, Nec, Recycling (MNR), Transport and Postal (TWP), and Coke (COK) in developing economies negatively and substantially contributed to the increase in the VPM of traditional trade. It is important to take advantage of strategic opportunities such as the Green Belt and Road Initiative to export cleaner production technologies to these sectors and their upstream enterprises in developing countries to help mitigate global climate change.

Finally, changes in foreign final demand and deepening integration into GVCs induced more domestic inputs of high emission intensity, such as those from Electricity, Gas and Water Supply (EGW), Other Non-Metallic (ONM), Basic Metals and Fabricated Metal (BAS) and Chemicals (CHE) in China. Therefore, on the one hand, China is encouraged to apply cleaner energy and conduct R&D in carbon reduction technologies and production technologies in these sectors to decrease their emission intensity and enhance their ability to gain value added. On the other hand, it is also necessary to promote the servicification of manufacturing and scale up the domestic intermediate inputs from KIBS to undertake more knowledge-intensive production tasks in GVCs to promote an increase in China's GVC position.

Our study can be promoted further in several aspects. First, the Analytical Activities of MNEs (AMNE) database has released ICIO tables that distinguish the production of MNEs and non-MNEs. Therefore, the dual effects of international trade could be studied more precisely based on the differences between domestically owned firms and foreign invested enterprises or among different production activities (Wang et al., 2021). Second, given the differences in the sectoral competitive advantage and development degree of each region within China, the heterogeneity of the economic and environmental effects of foreign trade on different regions could be investigated using a uniform IO framework integrating national value chains (NVCs) and GVCs. Third, the infrastructure system plays an important role in facilitating foreign trade but leads to massive carbon emissions when transporting goods. Embodied emission exports from Transport and Postal (TWP) ranked fifth among 22 sectors (Fig. 4), and an enormous portion of intermediate inputs from Coke, Refined Petroleum and Nuclear Fuel (COK) are also induced. Therefore, an interesting and significant extension can be made by combining China's regional IO framework with its infrastructure networks to analyze the regional comprehensive economic and environmental benefits. Donaghy, Beheshtian, Zhang, and Brown-Steiner (2021) provide a relevant reference. Fourth, China may also face a trade-off when substituting domestic intermediate inputs for foreign ones. Fifth, one limitation of this paper is that the WIOTs that we use cover only the 2000–2014 period. However, the WIOTs can still satisfy our research purposes of studying the imbalance in the imports and exports of China and ways to address this imbalance because the large gap between China and developed economies is a long-term issue and the national and sectoral development strategies proposed in this paper are still currently valid. Finally, the

[6] https://www.consilium.europa.eu/en/press/press-releases/2015/06/29/eu-china-climate-statement/

[7] https://www.mfa.gov.cn/web/ziliao_674904/tytj_674911/zcwj_674915/201908/t20190821_7949994.shtml

results of this paper would be more precise if we had distinguished the processing and general trade of China.

Data availability

Data will be made available on request.

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Appendix A

The effects of the driving factors in Eq. (12) can be formulated as follows

$$D_{VAX^s_{Vd}\_T} = exp\left[\sum_{i,j,r\neq s} \mathrm{W}_{ijr,T} ln\left(\frac{v_i^{s,1}}{v_i^{s,0}}\right)\right] \tag{A.1}$$

$$D_{VAX^s_{Ld}\_T} = exp\left[\sum_{i,j,r\neq s} \mathrm{W}_{ijr,T} ln\left(\frac{l_{ij}^{ss,1}}{l_{ij}^{ss,0}}\right)\right] \tag{A.2}$$

$$D_{VAX^s\_{Ye}\_T} = exp\left[\sum_{i,j,r\neq s} \mathrm{W}_{ijr,T} ln\left(\frac{y_i^{sr,1}}{y_i^{sr,0}}\right)\right] \tag{A.3}$$

where $\mathrm{W}_{ijr,\mathrm{T}} = \frac{\mathrm{L}\left(v_i^{s,1} l_{ij}^{ss,1} y_j^{sr,1} v_i^{s,0} l_{ij}^{ss,0} y_j^{sr,0}\right)}{\mathrm{L}\left(VAX_T^{s,1} VAX_T^{s,0}\right)}$, and v_i^s, l_{ij}^{ss}, and y_j^{sr} are the elements in the value added coefficient matrix $\widehat{V}$, domestic Leontief inverse matrix L and final demand matrix $\widehat{Y}$, respectively. $L(a,b) = \begin{cases} \frac{a-b}{lna-lnb} & a \neq b \\ a & a = b \end{cases}$ is the log-mean weight function, which was applied to promote the Divisia index decomposition method by Ang and Choi (1997) and obtain ideal decomposition results without residuals.

Regarding the change in country s's VPX of GVC, $D_{VAX^s_G}$ can be decomposed as follows:

$$D_{VAX^s\_G} = D_{VAX^s_{Vd}\_G} \bullet D_{VAX^s_{Ld}\_G} \bullet D_{VAX^s_{H}\_G} \bullet D_{VAX^s_{Ye}\_G} \tag{A.4}$$

The effects in Eq. (A.4) can be formulated as follows:

$$D_{VAX^s_{Vd}\_G} = exp\left[\sum_{i,j,r,k,t\neq s} \mathrm{W}_{ijkrt,G} ln\left(\frac{v_i^{s,1}}{v_i^{s,0}}\right)\right] \tag{A.5}$$

$$D_{VAX^s_{Ld}\_G} = exp\left[\sum_{i,j,r,k,t\neq s} \mathrm{W}_{ijkrt,G} ln\left(\frac{l_{ij}^{ss,1}}{l_{ij}^{ss,0}}\right)\right] \tag{A.6}$$

$$D_{VAX^s_{H}\_G} = exp\left[\sum_{i,j,r,k,t\neq s} \mathrm{W}_{ijkrt,\mathrm{G}} ln\left(\frac{h_{jk}^{sr,1}}{h_{jk}^{sr,0}}\right)\right] \tag{A.7}$$

$$D_{VAX^s_{Ye}\_G} = exp\left[\sum_{i,j,r,k,t\neq s} \mathrm{W}_{ijkrt,\mathrm{G}} ln\left(\frac{y_k^{rt,1}}{y_k^{rt,0}}\right)\right] \tag{A.8}$$

where $\mathrm{W}_{ijkrt,\mathrm{G}} = \frac{\mathrm{L}\left(v_i^{s,1} l_{ij}^{ss,1} h_{jk}^{sr,1} y_k^{rt,1} v_i^{s,0} l_{ij}^{ss,0} h_{jk}^{sr,0} y_k^{rt,0}\right)}{\mathrm{L}\left(VAX_G^{s,1} VAX_G^{s,0}\right)}$, and h_{jk}^{sr} is one element in the global industry linkage matrix H.

$D_{EEX^s\_G}$ can also be similarly decomposed; thus, the effects of the driving factors of $D_{VPX^s\_G}$ can be given as follows:

$$D_{VPX^s\_G} = D_{VAX^s_{Vd}\_G} \bullet \frac{1}{D_{EEX^s_{Fd}\_G}} \bullet \frac{D_{VAX^s_{Ld}\_G}}{D_{EEX^s_{Ld}\_G}} \bullet \frac{D_{VAX^s_{H}\_G}}{D_{EEX^s_{H}\_G}} \bullet \frac{D_{VAX^s_{Ye}\_G}}{D_{EEX^s_{Ye}\_G}}$$

$$= D_{Vd\_G} \bullet D_{Fd\_G} \bullet D_{Ld\_G} \bullet D_{H\_G} \bullet D_{Ye\_G} \tag{A.9}$$

where D_{Vd_G}, D_{Fd_G}, D_{Ld_G}, D_{H_G}, and D_{Ye_G} are the domestic value added coefficient effect, domestic emission coefficient effect, domestic industry linkage effect, global industry linkage effect and foreign final demand effect that contribute to the change in VPX^s_G, respectively.

Similarly, the effects of the driving factors on changes in country s's VPM of traditional trade and GVC can be written as follows:

$$D_{VPM^s\_T} = D_{Ve\_T} \bullet D_{Fe\_T} \bullet D_{Le\_T} \bullet D_{Yd\_T} \tag{A.10}$$

$$D_{VPM^s\_G} = D_{Ve\_G} \bullet D_{Fe\_G} \bullet D_{Le\_G} \bullet D_{H\_G} \bullet D_{Yd\_G} \tag{A.11}$$

Taking the factor effects of $D_{VPM^s\_G}$ as an example, D_{Ve_G}, D_{Fe_G}, D_{Le_G}, D_{H_G}, and D_{Yd_G} are the foreign value added coefficient effect, foreign emission coefficient effect, foreign industry linkage effect, global industry linkage effect and domestic final demand effect that contribute to the change in VPM^s_G, respectively.

The driving factor effects on changes in the aggregate VPM and VPX can be derived from the driving factor effects on changes in VPM and VPX at the above production activity level. For example, the numerator of $D_{VPX^s} = \frac{D_{VAX^s}}{D_{EEX^s}}$ can be decomposed into the following:

$$D_{VAX^s} = D_{VAX^s_{Vd}} \bullet D_{VAX^s_{Ld}} \bullet D_{VAX^s_{H}} \bullet D_{VAX^s_{Ye}} \tag{A.12}$$

Each effect in Eq. (A.12) can be formulated as follows:

$$D_{VAX^s_{Vd}} = exp\left[ln\left(D_{VAX^s_{T,Vd}}\right) \bullet \frac{L\left(VAX^{s,1}_T VAX^{s,0}_T\right)}{L\left(VAX^{s,1} VAX^{s,0}\right)} + ln\left(D_{VAX^s_{G,Vd}}\right) \bullet \frac{L\left(VAX^{s,1}_G VAX^{s,0}_G\right)}{L\left(VAX^{s,1} VAX^{s,0}\right)}\right] \tag{A.13}$$

$$D_{VAX^s_{Ld}} = exp\left[ln\left(D_{VAX^s_{T,Ld}}\right) \bullet \frac{L\left(VAX^{s,1}_T VAX^{s,0}_T\right)}{L\left(VAX^{s,1} VAX^{s,0}\right)} + ln\left(D_{VAX^s_{G,Ld}}\right) \bullet \frac{L\left(VAX^{s,1}_G VAX^{s,0}_G\right)}{L\left(VAX^{s,1} VAX^{s,0}\right)}\right] \tag{A.14}$$

$$D_{VAX^s_{H}} = exp\left[ln\left(D_{VAX^s_{G,H}}\right) \bullet \frac{L\left(VAX^{s,1}_G VAX^{s,0}_G\right)}{L\left(VAX^{s,1} VAX^{s,0}\right)}\right] \tag{A.15}$$

$$D_{VAX^s_{Ye}} = exp\left[ln\left(D_{VAX^s_{T,Ye}}\right) \bullet \frac{L\left(VAX^{s,1}_T VAX^{s,0}_T\right)}{L\left(VAX^{s,1} VAX^{s,0}\right)} + ln\left(D_{VAX^s_{G,Ye}}\right) \bullet \frac{L\left(VAX^{s,1}_G VAX^{s,0}_G\right)}{L\left(VAX^{s,1} VAX^{s,0}\right)}\right] \tag{A.16}$$

The numerator and denominator D_{EEX^s} can be aggregated similarly.

Therefore, the aggregate changes of country s can be written as follows:

$$D_{VPX^s} = D_{Vd} \bullet D_{Fd} \bullet D_{Ld} \bullet D_{H} \bullet D_{Ye} \tag{A.17}$$

$$D_{VPM^s} = D_{Ve} \bullet D_{Fe} \bullet D_{Le} \bullet D_{H} \bullet D_{Yd} \tag{A.18}$$

Appendix B

Table B.1
The country list by economy groups.

No	Acronym	Country	Economy
1	AUS	Australia	Other Developed Economies
2	AUT	Austria	EU15
3	BEL	Belgium	EU15
4	BGR	Bulgaria	Other Developing Economies
5	BRA	Brazil	Other BRICS
6	CAN	Canada	Other Developed Economies
7	CHE	Switzerland	Other Developed Economies
8	CHN	China	China
9	CYP	Cyprus	Other Developed Economies
10	CZE	Czech Republic	Other Developed Economies
11	DEU	Germany	EU15
12	DNK	Denmark	EU15
13	ESP	Spain	EU15
14	EST	Estonia	Other Developed Economies
15	FIN	Finland	EU15
16	FRA	France	EU15
17	GBR	United Kingdom	EU15
18	GRC	Greece	EU15

(continued on next page)

Table B.1 (*continued*)

No	Acronym	Country	Economy
19	HRV	Croatia	Other Developed Economies
20	HUN	Hungary	Other Developed Economies
21	IDN	Indonesia	Other Developing Economies
22	IND	India	Other BRICS
23	IRL	Ireland	EU15
24	ITA	Italy	EU15
25	JPN	Japan	East Asia
26	KOR	Korea	East Asia
27	LTU	Lithuania	Other Developed Economies
28	LUX	Luxembourg	EU15
29	LVA	Latvia	Other Developed Economies
30	MEX	Mexico	Other Developing Economies
31	MLT	Malta	Other Developed Economies
32	NLD	Netherlands	EU15
33	NOR	Norway	Other Developed Economies
34	POL	Poland	Other Developed Economies
35	PRT	Portugal	EU15
36	ROU	Romania	Other Developing Economies
37	RUS	Russia	Other BRICS
38	SVK	Slovak Republic	Other Developed Economies
39	SVN	Slovenia	Other Developed Economies
40	SWE	Sweden	EU15
41	TUR	Turkey	Other Developing Economies
42	TWN	Taiwan	East Asia
43	USA	United States	USA
44	ROW	The rest of the world	Other Developing Economies

Table B.2
Sector integration in the WIOTs released in 2016.

No	Acronym	Sector	Sector for short	Integration of sectors
c1	AGR	Agriculture, Hunting, Forestry and Fishing	Agriculture	r1-r3
c2	MIN	Mining and Quarrying	Mining	r4
c3	FOO	Food, Beverages and Tobacco	Food	r5
c4	TL	Textiles, Textile Products, Leather, Leather and Footwear	Textile and Leather	r6
c5	WOO	Wood and Products of Wood and Cork	Wood	r7
c6	PUL	Pulp, Paper, Paper, Printing and Publishing	Pulp and Paper	r8-r9
c7	COK	Coke, Refined Petroleum and Nuclear Fuel	Coke	r10
c8	CHE	Chemicals and Chemical Products	Chemicals	r11-r12
c9	RUB	Rubber and Plastics	Rubber and Plastics	r13
c10	ONM	Other Non–Metallic Mineral	Other Non–Metallic	r14
c11	BAS	Basic Metals and Fabricated Metal	Basic Metals and Fabricated Metal	r15-r16
c12	EOE	Electrical and Optical Equipment	Electrical and Optical Equipment	r17
c13	EE	Electrical Equipment	Electrical Equipment	r18
c14	MACN	Machinery, Nec	Machinery, Nec	r19
c15	TRE	Transport Equipment	Transport Equipment	r20-r21
c16	MNR	Manufacturing, Nec; Recycling	Manufacturing, Nec; Recycling	r22-r23
c17	EGW	Electricity, Gas and Water Supply	Electricity, Gas and Water Supply	r24-r25
c18	CON	Construction	Construction	r27
c19	WRE	Wholesale and retail trade and repair of motor vehicles and motorcycles	Wholesale and retail	r28-r30
c20	TWP	Transport, Warehousing and Support Activities for Transportation, Postal and Courier activities	Transport and Postal	r31-r35
c21	KIBS	Knowledge-Intensive Business Services	Knowledge-Intensive Business Services	r39-r41, r45-r49
c22	OSE	Other Services	Other Services	r36-r38, r42-r44, r50-r56

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