Carbon transfer within China: Insights from production fragmentation

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Abstract

Production fragmentation not only reshapes trade patterns but also reallocates trade-related emissions. This study employs China's multi-regional input-output tables for 2007, 2010 and 2012 to explore the effect of production fragmentation on virtual carbon trade derived from three trade patterns, i.e. final goods trade, intermediate goods trade for the final stage of production, and value chain-related trade. Results showed that inter-provincial trade within China reduced the national carbon emissions by 208 Mt and 114 Mt in 2007 and 2012. The first two trade patterns contributed to the reduction, while value-chain-related trade resulted in carbon growth. The four trillion yuan stimulus package promoted the development of energy intensive industries while inter-provincial trade increased national carbon emissions by 247 Mt in 2010. Moreover, this study revealed a list of provinces, trade patterns and sectors with the high carbon reduction potential.

Keywords: Production fragmentation; Carbon emissions; Multi-regional input-output analysis; Value chain

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1. Introduction

Due to the lower production cost and looser environmental regulations, the less developed regions have become the destinations of the developed regions to outsource the production process (Su and Ang, 2014). Similarly, the carbon emissions of some provinces in China are affected by the outsourcing of environmental pollution (Feng et al., 2013). At the 2015 Paris Summit, China committed to reducing the carbon intensity by 60% - 65% in 2030 compared to the 2005 level. Meanwhile, China's 13th Five-Year plan set a target to reduce the national carbon intensity by 18% by 2020 compared to the 2015 level (State Council of China, 2015). Regional reduction targets of carbon intensity varies according to the economic development level during 13th Five-Year period (2016-2020), ranging from 12% in the less developed western provinces to 20.5% in the east coast provinces (Liu et al., 2016). However, carbon emissions of a province is determined by a large number of factors. These include not only its economic development, population, physical geography, industrial structure and natural resources, but also its trade with other regions (Dietzenbacher et al., 2012; Wang H, 2017). Hence, the local government should take the environmental effect of inter-provincial trade into account when undertaking carbon reduction activities. With the development of production fragmentation, trade patterns is reshaped and the new trade patterns is bound to bring changes to carbon transfer among provinces (Meng et al., 2013; Yune et al., 2016; Yan et al., 2015). The aim of this paper is to track the carbon transfer derived from inter-provincial trade activities within China from the perspective of production fragmentation.

This study builds on growing literature on the carbon emissions embodied in trade within China (e.g., Dietzenbacher et al., 2012; López et al., 2013a; Meng et al., 2013; Su and Ang, 2014; Su et al., 2012; Pei et al., 2012; Pei et al., 2017). Previous studies mainly focus on the driving forces of carbon emissions induced by trade (e.g., Zhang, 2014) as well as the sources and destinations of carbon transfer (e.g., Feng et al., 2013; He et al., 2007). A region's position and participation level in supply chains affect its virtual carbon emissions trade (Meng et al., 2013). With the development of production fragmentation, intermediate goods cross provincial borders many times before they are delivered to the final users (Pei et al., 2015). Therefore, all participants (rather than sources and destinations) in the production network may be responsible for the environmental cost for the consumers of products. The main focuses of this study are: to explore the new path of carbon transfer and to identify key sectors responsible for environmental problem induced by trade.

Production fragmentation was firstly introduced to explore the environmental effects of carbon flows (Taylor, 2005). Since then, there are two main research streams on the production fragmentation in China. From the perspective of global production networks, previous studies mainly focused on China's virtual carbon flows in the global value chain (Wang et al.,2017a), carbon embodied in processing export and normal export (Dietzenbacher et al., 2012; He, 2007). From the perspective of domestic production networks, most studies concentrate on the virtual carbon flows of Chinese regions in the domestic value chain (e.g., Meng et al., 2015; Pei et al., 2015). For instance, Meng et al. (2015) suggested that most inland regions have been deeply involved in domestic supply chains by providing a large amount of intermediate products to other regions. As a result, the embodied CO_2 emissions in these regions' outflow have also rapidly increased. Nevertheless, very few studies attempted to examine the effects of the inter-provincial trade on the carbon emission of China. This paper examines the role of inter-provincial trade in achieving the national target of carbon emission (i.e. as a driver or a barrier).

Recently, China enters an era of "new normal" economic growth, in which the production and consumption structure has changed considerably (Su and Ang, 2017). Domestic trade within China has grown rapidly[2] which presents some new features. For example, the carbon emissions embodied in China's exports have declined and the carbon transfer through inter-provincial trade in China have reversed since the global financial crisis (Mi et al., 2017). The less developed regions, such as the Southwest China, have shifted from being a net emission exporter to being a net emission importer. Mi et al. (2017) explained this novel conclusion from the perspective of new economic development patterns in China as well as the change of China's role in the global trade. This paper attempts to extend Mi et al.'s study by considering the effects of changes to production fragmentation on the carbon transfer. We evaluate how the global financial crisis affects the carbon emissions embodied in inter-provincial trade from the perspective of different trade patterns over the period 2007-2012.

Closely related to López et al. (2013b) and Arce et al.(2012), this paper isolates three trade patterns from the perspective of production stage, namely trade in final

[2] The volume of domestic trade in 2017 (36626billion Yuan) is more than four times that of 2007 (8921billion Yuan). Data sources: National Bureau of Statistics, http://data.stats.gov.cn/easyquery.htm?cn=C01

goods, trade in intermediate goods for the last stage of production and value chain related trade. For the first two patterns, goods are absorbed by the importers. They are also defined as traditional Ricardian trade and reflect the direct value added trade pattern (Borin and Mancini, 2015; Wang et al., 2017b). For the last trade pattern, imported intermediate goods are processed and then re-exported as inputs for other region's production (Borin and Mancini, 2015; Dean and Lovely, 2010). In addition, this paper introduce the Structural Decomposition Analysis (SDA) to evaluate the carbon transfer from 2007 to 2012.

SDA is a widely used approach to analyze the driving forces of carbon emissions embodied in trade (Ang et al., 2016; Su et al., 2012; Su and Ang, 2016; Su and Thomson, 2016; Wang et al., 2017a; Yan and Dietzenbacher, 2014; Yan et al., 2015). Various decomposition approaches have been proposed by previous studies, such as D&L approach (Dietzenbacher and Los, 1998), the Logarithmic Mean Divisia Index (LMDI) model (Ang et al., 2003; Su and Thomson, 2016), and two-polar decomposition approach (Fan and Xia, 2012; Mi et al., 2017). According to the guidelines on the selection in SDA approach proposed by Su et al. (2012), we employ the LMDI method to examine the driving forces of embodied cabon emissions of trade within China.

We also examine whether trade within China is harmful to the environment by means of the Balance of Avoided Emissions (BAE), which was proposed by López et al. (2013a). The BAE differentiates between provincial carbon emissions embodied in exports with other provinces minus the emissions avoided by imports from other provinces, the CO_2 emissions that would be emitted locally if the imported products was produced by itself. A positive BAE indicates the trade within China would be an incentive for China's carbon emissions and a negative BAE shows the production fragmentation of trade allows emissions savings. One branch of previous studies evaluate the balance of avoided emissions used bi-regional models (Arce et al., 2012; Arto et al., 2014; Dietzenbacher and Mukhopadyay, 2007; Liu et al., 2016; López et al.,2013b; Hao et al., 2013; Peters et al., 2011). MRIO analysis were introduced to examine the balance of avoided emissions driven by international trade which would mitigate the underestimation problem by bi-regional model. Kanemoto et al. (2012) and Turner et al. (2007) used a Global MRIO model were used to compute the BAE. Chen and Chen (2011) divided the world in three regions; López et al. (2018) estimated the effects of international trade on BAE of seven regions under free trade agreement. Zhang et al. (2014) employed a Chinese MRIO model and clarified that the interregional trade contributed to the decrease of national carbon emission for 1997 and 2007, while the results would be underestimated when considering provincial positions and contributions in supply chain. To enrich the literature, this paper applies Zhang et al.'s analysis method (2017) to assess the inter-provincial trade on provincial and national carbon emissions from the perspective of production fragmentation. The main conclusions are summarized as below.

First, we adopt the method proposed by Wang et al. (2017), which decomposes the Leontief inverse matrix to distinguish the emission induced by pure local consumption from three different trade production activities. The results show that carbon emissions embodied in international export declined by 6% in 2010 compared to the 2007 level, as a result of the global financial crisis in 2008. On the contrary, the carbon emissions embodied in inter-provincial trade grew by 52% from 2007 to 2012, among which, value chain related trade remains the largest contributor.

Second, this paper tracks the carbon transfer by inter-provincial trade within China. Results showed that the carbon transfer is mainly concentrated in the south and east of China, while the provinces in the northwest (except Xinjiang) and southwest are less participated in the inter-provincial trade. In addition, the path of carbon transfer varied according to trade patterns. For instance, one of the major paths of carbon transfer by final goods trade is from Xinjiang to Beijing and Tianjin. This is in accordance with the North Channel of West-East electricity transmission project where power grid of Xinjiang lies in the headstream and Jing-Jin-Ji are destinations.

Finally, we evaluate how production fragmentation affect China's carbon emission from inter-provincial trade depending on comparative emission advantages of different provinces and sectoral composition of trade. This study revealed that China's production fragmentation generates national emissions savings by 114Mt, while the value chain related trade offsets this reduction. Moreover, stimulated by the four trillion yuan stimulus package in 2008, the effect of production fragmentation on China's carbon emissions shows a curve from negative (-208Mt) in 2007 to positive (247Mt) in 2010. This result may be attributed to the infrastructure developments which caused the growth of both energy consumption and carbon intensity in heavy industries.

The reminder of this paper is as follows: Section 2 introduces the methodology and data materials, and the main results of embodied emissions and the environmental effects of different trade patterns are presented in Section 3. Section 4 draws the major conclusion and policy implications.

2. Methodology and Data

2.1 Method of trade patterns decomposition

This section explains the methodology of decomposing different trade patterns and tracing the balance of embodied emissions and avoided emissions, based on a country composed of *G* provinces and *N* sectors. These provinces connected with other provinces and foreign countries through trade. The economic linkage is presented as a multi-regional input-output table (Table S.1). We distinguish the output of domestic activity and different trade patterns by decomposing the Leontief inverse matrix. The detailed method of decomposition of total output is presented in Appendix A.

In terms of trade, the exports from province *s* to province *r* are $T^{sr} = T\_f^{sr} + T\_i^{sr} + T\_v^{sr}$, where $T\_f^{sr} = Y^{sr}$ defines trade in final products. The trade partner would directly absorb the exported products, and the exporter is located in the last stage of productions. Trade in intermediate products for the last stage of production is $T\_i^{sr} = A^{sr}L^{rr}Y^{rr}$. A^{sr} is the input coefficient matrix that represents the intermediate use in province *r* of goods produced in province *s*. T_v^{sr} is the narrowly defined value chain related trade (Wang et al., 2017). The traded products cross the provincial or national border more than once, which may be finally absorbed by a domestic province or further processed and exported to foreign counties. The former is $T\_d^{sr} = A^{sr}L^{rr}\sum_{t\neq r}^{G}A^{rt}B^{tr}Y^{rr} + A^{sr}\sum_{t\neq r}^{G}B^{rt}Y^{tr} + A^{sr}\sum_{t}^{G}B^{rt}\sum_{t\neq r}^{G}Y^{tu}$, which named the domestic value chain related trade, and the latter is $T\_g^{sr} = A^{sr}\sum_{t}^{G}B^{rt}EX^{t}$, which indicates the global value chain related trade.

We define the carbon intensity of the sector *i* of province *s* as $f_i^s = e_i^s/x_i^s$, where e_i^s represents the carbon emissions of the sector *i* of province *s*, x_i^s represents the final output of the sector *i* of province *s*,. F^s is a diagonal matrix made up of f_i^s. The gross carbon emissions of province *s* is

$$E^s = F^s X^s = F^s L^{ss} Y^{ss} + F^s L^{ss} EX^s + F^s L^{ss}\sum_{s\neq r}^{G} T\_f^{sr} + F^s L^{ss}\sum_{s\neq r}^{G} T\_i^{sr} + F^s L^{ss}\sum_{s\neq r}^{G} T\_v^{sr} \quad (1)$$

The gross carbon emissions of province *s* are decomposed into five terms. The first term represents emissions induced by economic activity within province *s* that has no relation with the inter-provincial or international production fragmentation. The second terms represents emissions induced by trade in final products, which are absorbed by the foreign countries. The last three terms represent the emissions induced by different trade patterns.

Consequently, the domestic emissions embodied in exports from province *s* to province *r* is

$$EEX^{sr} = F^s L^{ss} T^{sr} = F^s L^{ss} T\_f^{sr} + F^s L^{ss} T\_i^{sr} + F^s L^{ss} T\_v^{sr} \quad (2)$$

Equation (2) decomposes the emissions embodied in gross exports from province *s* to province *r* into three terms by the trade pattern, the traditional final products trade, the traditional intermediate products trade, the domestic value chain related trade and the global value chain related trade. Therefore, the balance of embodied emissions (BEE) can be revealed as:

$$BEE^{sr} = EEX^{sr} - EEX^{rs}$$

$$= \underbrace{(F^sL^{ss}T_f{}^{sr} - F^rL^{rr}T_f{}^{rs})}_{(3-1)} + \underbrace{(F^sL^{ss}T_i{}^{sr} - F^rL^{rr}T_i{}^{rs})}_{(3-2)}$$

$$+ \underbrace{(F^sL^{ss}T\_d^{sr} - F^rL^{rr}T\_d^{rs})}_{(3-3)} + \underbrace{(F^sL^{ss}T\_g^{sr} - F^rL^{rr}T\_g^{rs})}_{(3-4)} \quad (3)$$

Term (3-1) represents the balance of emissions embodied in traditional final products trade; term (3-2) represents the balance of emissions embodied in traditional intermediate products trade; term (3-3) represents the balance of emissions embodied in domestic value chain related trade; term (3-4) represents the balance of emissions embodied in global value chain related trade.$BEE^{sr} > 0$ means the bilateral trade promotes the carbon emissions of province *s*; otherwise, the bilateral production fragmentation contributes to a decrease in the carbon emissions of province *s*. The effects of position in the production fragmentation on carbon emissions of province *s* is $BEE^s = \sum_{r \neq s}^{G} EEX^{sr} - \sum_{r \neq s}^{G} EEX^{rs}$, which is defined as total emissions embodied in exports of province *s* minus total emissions embodied in imports of province *s*. $BEE^s > 0$ means the position in the production fragmentation contributes to an increase in the carbon emissions of province *s*. $BEE^s < 0$ means the position in the production fragmentation promotes a decrease in the carbon emissions of province *s*. Nevertheless, it is impossible to use BEE to know the influence of interprovincial trade on national emissions because the aggregation of BEE for all countries is always zero ($\sum_s^G BEE^s = 0$).

The effects of production fragmentation on the national emissions are evaluated by the difference between emissions embodied in exports and emissions avoided by imports (balance of avoided emissions, BAE) (Dietzenbacher and Mukhopadhyay, 2007; López et al., 2013). The emissions avoided by imports of province s from province r through different trade patterns is $EAI^{sr}=F^{s}L^{ss}T^{rs}$. The balance of avoided emissions (BAE) is

$$BAE^{sr}=(EEX^{sr}-EAI^{sr})+(EEX^{rs}-EAI^{rs})$$

$$=\underbrace{(F^{s}L^{ss}-F^{r}L^{rr})T_{f}{}^{sr})+(F^{s}L^{ss}-F^{r}L^{rr})T_{i}{}^{sr})+(F^{s}L^{ss}-F^{r}L^{rr})T_{v}{}^{sr})}_{4-1}$$

$$+\underbrace{(F^{r}L^{rr}-F^{s}L^{ss})T\_f^{rs})+(F^{r}L^{rr}-F^{s}L^{ss})T\_i^{rs})+(F^{r}L^{rr}-F^{s}L^{ss})T\_v^{rs})}_{4-2} \quad (4)$$

Term (4-1) explains the pollution heaven hypotheses (PHH) from the perspective of production structure and carbon intensity of the exports from province s to province r, which can be further divided into three trade patterns. Term (4-2) explains the PHH from the perspective of production structure and carbon intensity of the imports of province s from province r, which can also be further divided according to three trade patterns. The expression of gross balance of avoided emissions is presented as below.

$$\text{BAE}=\sum_{s}^{G}\sum_{r\neq s}^{G}BAE^{sr} \quad (5)$$

A positive *BAE* means the pollution haven hypothesis holds; and a negative *BAE* means the interprovincial trade contributes to a decrease in gross emissions.

2.2 Data

Two main datasets were used in this paper: multi-regional input-output tables of China and corresponding carbon emissions data. The 2007, 2010 and 2012 Chinese MRIO tables are compiled by the Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences (Liu et al., 2012; Liu et al., 2014; Liu et al., 2018). The economics data in the 2012 MRIO model is updated to the year

2007 and 2010. Chinese MRIO tables 2007 and 2010 have only 30 regions, while MRIO tables 2012 added Tibet and had 31 regions. In order to ensure the consistency of the results, we calculated the carbon emissions embodied in trade using the MRIO table 2012 with 31 regions, only kept the calculation results of 30 provinces and dropped that of Tibet. To match the carbon emissions data with the MRIO data, the MRIO tables are merged into 27 sectors from 30 sectors. The data of carbon emissions of 30 regions in 2007, 2010 and 2012 were from emission inventories complied by CEADS (www.ceads.net) (Shan et al., 2017). IPCC Sectoral Emission Accounting Approach was used and emission inventories were calculated based on the data of energy consumption from Statistical Yearbook of regions and Energy Statistical Yearbook of China for the target year.

3. Results

3.1 Preliminary results on embodied emissions

In this section, we decompose carbon emissions into pure domestic economic activities, direct export to foreign countries and three trade patterns and presents the driving factors of carbon emissions changes from 2007 to 2012.

3.1.1 Decomposition of China's emissions

China has been the largest carbon emitter in the world since 2006 (Liu et al., 2015; Thompson et al., 2016) and is consequently present significant pressure on carbon reduction domestically and internationally. Fig. 1 shows that China's carbon emissions increased from 6,547Mt in 2007 to 9,647Mt in 2012 with an average rate of 9.5% per year. Global financial crisis erupted in 2008 and seriously affected the export volume of China, which declined by 12.3% in 2009 as the level of 2007[3]. As a result, the carbon emissions embodied in China's export dropped from 917Mt in 2007 to 883Mt in 2010. As a response to this crisis, the Chinese government introduced a four trillion yuan (approximately 586 billion USD) stimulus package in November 2008 which mainly aimed at fixed assets and infrastructure developments, such as high-speed rail network, rural infrastructure and city electrical grid. The development of these carbon-intensive industries contributes to carbon emissions induced by domestic economic activity within China, which raise by 52% in 2012 compared with 2007.

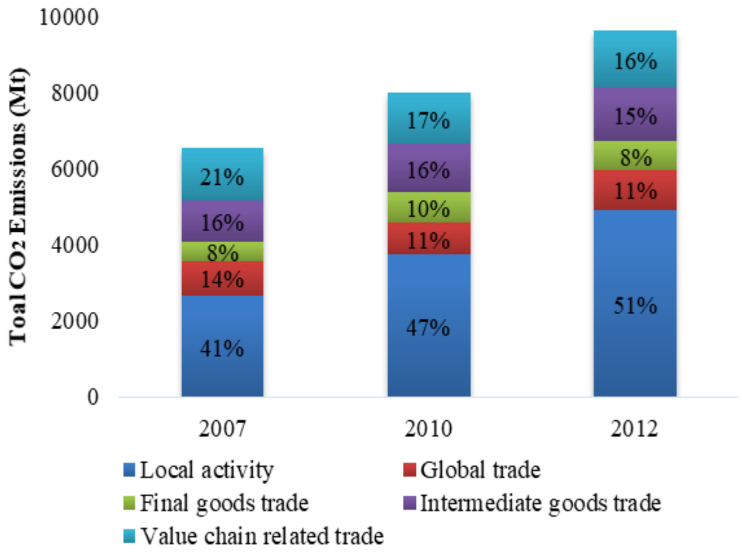

Fig. 1. Decomposition of China's carbon emissions in 2007, 2010 and 2012

Notes: global trade indicates the final goods trade for foreign countries; final goods trade, intermediate goods trade and value chain related trade indicates different trade patterns of inter-provincial trade.

Carbon emissions embodied in inter-provincial trade maintained steady growth by 24% from 2007 to 2012. For different trade patterns, the carbon emissions

[3] Data sources: National Bureau of Statistics of China, http://data.stats.gov.cn/easyquery.htm?cn=C01.

embodied in final goods trade, intermediate goods trade and value chain related traded increased by 50%, 31% and 9% from 2007 to 2012, respectively. Value chain related trade has always been the largest share among the inter-provincial trade. This highlights the crucial role of value chain related trade in carbon emissions reduction. Indeed, the responsibility of carbon reduction should be shared with all participants in the value chain instead of the producer of final products. This paper further compares the embodied emissions of each province as well as the role of production fragmentation on national and provincial emissions through inter-provincial trade.

3.1.2 Decomposition of provincial emissions

Fig. 2 shows the decomposition of carbon emissions of 30 provinces in China in 2012. Among these 30 provinces, Shandong (843 Mt), Hebei (737 Mt) and Jiangsu (657 Mt) are the top three emitters. The emissions of these three regions shows different features. As a populous region, 66% of Shandong's total carbon emissions are induced by local final demand. The main sources of carbon embodied in local activities include the production and supply of electric power and hot power (45%), metals smelting and pressing (16%) and transportation and warehousing (8%), among which the heavy industry and metals digging are high-carbon-intensive industries. Besides, Shandong is located in the coastal of Bohai Sea and the Yellow Sea and has geographical advantage of maritime transportation for export. It was the fifth region of total export volumes in China in 2016 (National Bureau of Statistics, 2017). Hence carbon emissions induced by export of Shandong is the second largest part of the provincial emissions (12%), which is up to 102Mt.

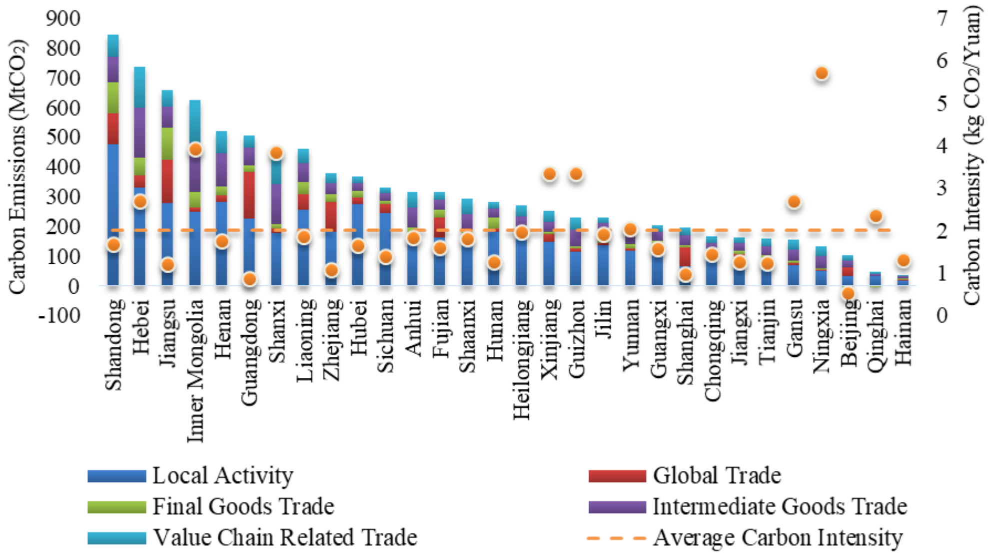

Fig. 2. Decomposition of carbon emission and carbon intensity of 30 provinces of China in 2012

The second largest carbon emitter is Hebei, the emissions of which is mainly induced by the domestic final demand and the trade in intermediate products, except the carbon emissions induced by local activities. Compared with Shandong, the higher proportion of the trade in intermediate products may be the results of industry structure, such as steel industry. Hebei is the largest steel producer in China and deliver 24% of national steel products to other provinces, like Liaoning, Beijing and Jiangsu, for further processing. Metals smelting and pressing sector accounts for 52% (82.6Mt) of carbon emission is induced by intermediate goods trade. Similar to Hebei, Shanxi and Inner Mongolia are also rich in mineral and metal resources which promote the trade in related intermediate products and increase the domestic carbon emissions.

Jiangsu is the third largest carbon emitter which has large volume of exports to foreign countries due to the geographical benefits along the coast. This has resulted in the growth of emissions induced by export trade. In addition to Jiangsu, the provinces whose share of carbon emissions induced by export more than 20% are all the coastal regions of China, such as Guangdong, Shanghai, Fujian and Zhejiang. Owing to "Open and Reform" policy of China in 1980s and advantages of geographical locations, China's coastal cities have access to global markets. With development of global production fragmentation, they become the most attractive locations for private manufacturing firms (Feng et al., 2013; Zheng et al., 2014). The coastal provinces of China emit more carbon dioxide and suffer more serious environmental pollution due to the foreign consumption (Zheng and Kahn, 2017).

We also analyzed carbon emission of each individual province from the perspective of trade patterns. For example, the share of carbon emissions induced by final goods trade of Chongqing and Jiangsu is more than 20% of the total provincial emissions. Carbon emissions induced by the intermediate goods for the last stage of production accounts for more than 25% of total carbon emissions in Ningxia and Qinghai which are caused by their nature resources endowment. Taking Ningxia as an example, the proven coal reserves is up to 30 billion tons, and the coal mining and washing industry contributes to 4.4 Mt carbon emissions. The share of carbon emissions induced by the value chain related trade is more than 30% in Inner Mongolia and Shanxi. Both of these two regions are rich in coal and mineral products which need further processing and provide these energy-intensive and low-value-added products to coastal and developed provinces (Feng et al., 2013).

To discuss the driving forces of embodied CO_2 emissions, the SDA approach is employed in this study to examine the changes in embodied emissions. From a nationwide view, the embodied emissions of 30 provinces increased by 10% from 2007 to 2012 mainly due to change in export. While the carbon intensity and production technology would have offset embodied emissions by 53% and 6%, respectively, which is determined by the clean technology development. As the impact of the global financial crisis on Chinese exports recedes, the growth of export raised by nearly 5 times for the period between 2010 and 2012 as that of the first period. National embodied emissions raised by 10% from 2010 to 2012. At the same period, the dividend of carbon emission reduction brought by the adjustment of industrial structure began to appear. Production technology offset the growth by 75%. From a provincial perspective, results show that Jiangsu, Zhejiang and Shandong dealt with the largest increases in emissions embodied in trade, which is mainly determined by the changes in export. By contrast, some provinces enjoy a drop in emissions that is embodied in trade over this period, such as Inner Mongolia from 2010 to 2012. The main contribution is the change in carbon intensity and decline in export. For most provinces, advanced production technology contributes a decline on the embodied emissions. While the production technology change also stimulates the embodied emissions for Beijing, Tianjin and Shanghai, etc., because the growth in the share of intermediate inputs per unit of outputs (Xu and Dietzenbacher, 2014).

3.2 Provincial balance of embodied emissions by trade pattern

Considering the effect of production fragmentation, the carbon transfer by different trade patterns reflects various directions. Fig. 3 shows the emissions induced by imports and exports through different trade patterns of 30 provinces of China.

From the perspective of imports and exports, Zhejiang was the largest net importer with 196Mt embodied carbon emissions, of which 56% embodied carbon emissions was from the value chain related trade. Besides, it indicates that Zhejiang is in the intermediate link of production and products which crosses borders many times before they are delivered to the final users through inter-provincial trade and contributes most to carbon emissions of Zhejiang. Similarly, Jiangsu, Shanghai and Chongqing are the major importers who import more than 100Mt CO_2 through inter-provincial trade. All these provinces are consumption-oriented provinces with advanced technologies and booming economics. However, the direction of carbon transfer may be different in terms of trade patterns. For Beijing and Guangdong, they are always the importers. While for Jiangsu, it is an exporter of final goods.

Fig. 3. Decomposition of carbon emissions embodied in the import and export of 30 provinces of China in 2012

In terms of net export, the largest net exporter was Inner Mongolia with 280Mt embodied carbon emissions, of which 64% embodied carbon is from the value chain related trade. Meanwhile, Hebei and Shanxi export more than 100Mt CO_2 as net exporters. All of these regions are rich in natural resources, such as coal of Shanxi and Inner Mongolia. These provinces carry out intermediate goods processing and stimulate their local economy which leads to higher carbon emissions finally. However, the direction of net carbon transfer may vary according to trade patterns. For instance, although Shanxi is a net carbon exporter from the perspective of total trade, it is a net carbon importer in terms of the trade of final goods.

We also compared the top 5 net exporters and importers in 2007, 2010 and 2012 (Fig. 4). For net exporters, Inner Mongolia has always been the largest net exporter and its net carbon emissions has continued to grow during this period. The carbon emissions embodied in value chain related trade accounts for more than 50% of its net emissions. In addition, Hebei and Shanxi are always in the top 5, both of them are less developed provinces with rich resources. For the top 5 net importers, all of them are affluent provinces or coastal provinces including Zhejiang, Shanghai, Guangdong, Beijing and Tianjin. It is worth noting that coastal provinces import products and emissions from other provinces and further export products to foreign countries. In general, most developed regions are net importers of embodied emissions from trade, while developing regions are net exporters (Su and Ang, 2011).

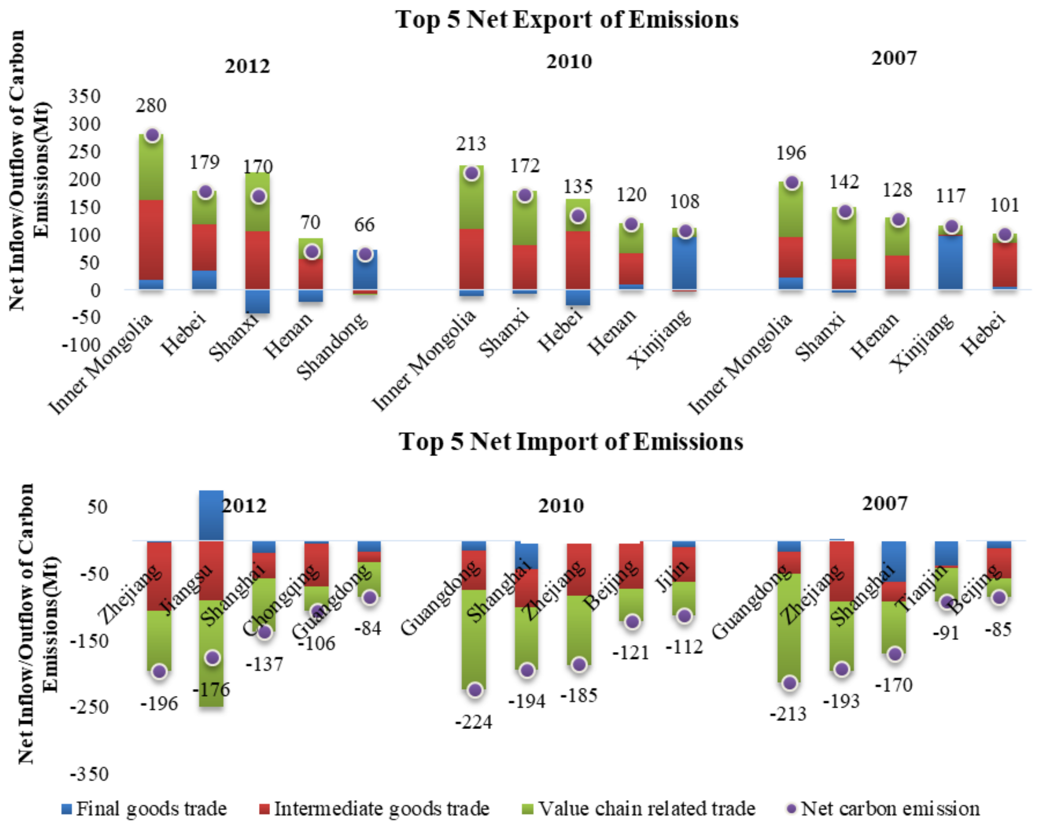

Fig. 4. Top 5 net importer province (row 1) and net exporter province (row 2) in 2012, 2010 and 2007

3.3 Bilateral carbon transfer by trade pattern

Further, this paper examined the effects of bilateral trade between provinces in China on provincial carbon emissions, respectively. Fig. 5 shows the top 10 net carbon flows of bilateral trade by different trade patterns in 2007, 2010 and 2012. Net carbon transfer in final goods trade maps the flows from northwest (Xinjiang) to north coast (Beijing-Tianjin) and east coast (Zhejiang, Jiangsu and Shanghai) (column 1). Xinjiang was the largest net exporter in 2007 and 2010 who mainly sent agricultural products and energy to Tianjin, Shanghai and Jiangsu whilst participated less in the national value chain. Jiangsu became the largest net exporter in 2012 and trade with central (Hubei, Hunan) and south coast (Guangdong) regions. The top 10 net carbon transfer by intermediate goods trade mainly concentrates in central regions, north coast and east coast (column 2). Hebei and Inner Mongolia are two largest net exporters who provide coal and metal products with developed provinces nearby, such as Beijing, Zhejiang and Jiangsu. Inner Mongolia has been one of the major electricity suppliers since the project of West-East electricity transmission implemented in 2001 and supply thermal power to Beijing-Tianjin. Similarly, the map of value chain related trade centers in central and northeast coast regions. Besides, the south coast province Guangdong is a large carbon importer by trading with southwest regions, such as Yunnan, Guizhou and Guangxi. This bilateral trade flow also shows the south channel of West-East electricity transmission project where power grid of Yunnan and Guizhou lies in the headstream and Guangdong is the destination. Overall, bilateral trades within China result in the growth of the carbon emissions in Xinjiang, Inner Mongolia and Shanxi who produce products for the Beijing-Tianjin, north coast and east coast provinces. It should be noted that bilateral trade within China is uneven geographically and provinces in the northwest (except Xinjiang) and southwest participated less in the trade.

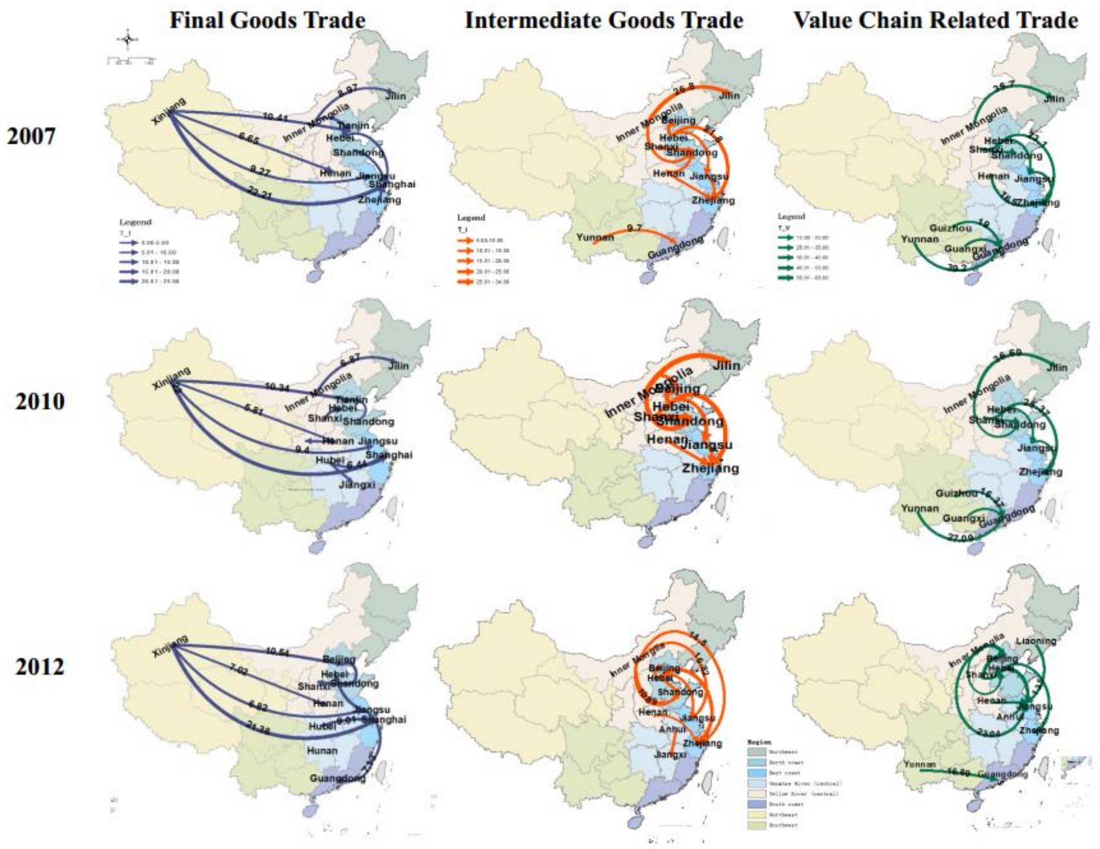

Fig. 5. The top 10 bilateral net carbon transfer flows by final goods trade, intermediate goods trade and value chain related trade in 2007, 2010 and 2012

Notes: blue line represents the net carbon flows by final goods trade, red line represents the net carbon flows by intermediate goods trade, green line represents the net carbon flows by value chain related trade; the values in the line is the net virtual carbon transfer between two regions; the thickness of a line indicates the net virtual carbon trade amount.

The effects of bilateral trade by trade patterns on carbon emissions of China is evaluated as the balance of avoided emissions by formula (4). In the final goods trade, trade between Shanghai and Shandong decreased China's carbon emissions by 4.14Mt. Export from Shanghai to Shandong decreased national emissions by 6.64Mt, while export from Shandong to Shanghai increased national emissions by 2.50Mt. It indicates carbon embodied in production of products in Shanghai which consumed in

Shandong is less than the emersions that would be generated if the products are produced in Shandong by 6.64Mt. This is because carbon intensity of Shanghai (0.96kgCO_2/Yuan) is much lower than that of Shandong (1.68 kgCO_2/Yuan). Therefore, import from provinces whose carbon intensity is lower than itself will decrease national carbon emissions, actually. On the contrary, import from provinces whose production technology is less advanced and carbon intensity is higher will increase national emissions. For example, the bilateral trade between Shanxi and Beijing contributes to a positive BAE by 11.66Mt. Export from Shanxi increase national emissions by 11.79Mt, although export from Beijing contributes a decline by 0.13Mt. In short, import from a province whose carbon intensity is lower and production technology is more advanced will be beneficial to the national carbon reduction.

3.4 Effects of inter-provincial trade on national carbon emissions

Furthermore, it is imperative to investigate how production fragmentation affect the national emissions through inter-provincial trade. In this section, we evaluate this effect by balance of avoided emissions (BAE). A negative BAE means the inter-provincial trade contributes to a decrease in carbon emissions of China, vice versa. First, we analyze the change of BAE of different trade patterns in 2007, 2010 and 2012 (Table 1). In 2010, inter-provincial trade increased BAE by 455 MtCO_2 compared with 2007 which are contributed by final goods trade and intermediate goods. This result may be attributed to the four trillion yuan stimulus package in 2008 which mainly aimed at infrastructure construction and caused the growth of both energy consumption and carbon intensity in heavy industries. Higher carbon intensity raised the carbon embodied in final goods and intermediate goods. These two trade patterns are less affected by production fragmentation, compared with the value chain related trade. In 2012, the impact of four trillion yuan on the growth of national carbon emissions showed a gradual weakening trend, not only in the carbon embodied in final goods trade, but also in the that of intermediate goods trade, which is consistent with the BAE in 2007. Nevertheless, BAEs of value chain related trade have always been positive for these years, which indicates the development of production fragmentation stimulates the national emissions.

Table 1 The effects of different trade patterns on national emissions ($MtCO_2$) in 2007, 2010 and 2012

	2007	2010	2012
Final goods trade	-313	-18	-182
Intermediate goods trade	-128	59	-39
Value chain related trade	233	207	107
Total BAE	-208	247	-114

Second, we analyzed the contributions of each province to BAE by trade pattern in 2012 (Fig. 6). In general, inter-provincial trade contributes to a decrease in carbon emissions of China by 114Mt in 2012. This is contrary to findings of Feng et al. (2013) which reported that the interprovincial trade within China cost a higher environmental pollution potentially, as the overall emissions might be higher. Inter-provincial trade within central coastal and south coast provinces and affluent cities such as Beijing, Tianjin, Shanghai and Jiangsu are the largest contributor to national emissions reduction. This is mainly due to their cleaner production technologies and lower carbon intensity. By contrast, northwest and central provinces (e.g. Xinjiang, Inner Mongolia and Hebei) contributed to the growth in national emissions. From the perspective of trade patterns, BAE of the same region may vary according to trade pattern. For example, export in final goods and intermediate goods from Beijing resulted in declines by -26Mt and -46Mt, while that in value chain related goods increased BAE by 22Mt.

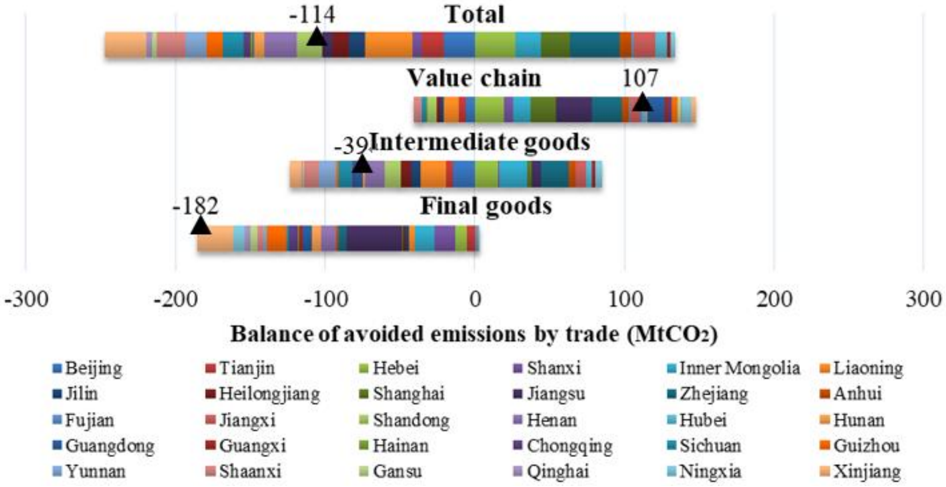

Fig. 6. Balance of avoided emissions by trade pattern in 2012

Furthermore, we evaluate the environmental effects of interprovincial trade on national and provincial carbon emissions of 30 provinces. By selecting the balance of avoided emissions (BAE) as the horizontal axis and the balance of embodied emissions (BEE) as the vertical axis, 30 provinces are divided into four quadrants (see Fig. 7). Fig. 7a shows the environmental effects of gross trade activities of 30 provinces. Six provinces are located in the first quadrant with a positive BAE and positive BEE which indicates the trade of these provinces with others promotes both local provincial and national carbon emissions. Inner Mongolia and Hebei as two representatives, both supply low-value-added and carbon-intensive products such as coal and mineral products to other provinces in China. Just like China and Russia, they become the manufactures to the world and also the pollution heaven (Zhang et al., 2017). There are ten provinces in the second quadrant with negative BAE and positive BEE. Most of them are less developed provinces in central and northeast regions. For instance, Shanxi provides services and products to others and results in higher local emissions. The most ideal provinces are in the third quadrant. Trade in these provinces contributes to a decrease in both provincial and national carbon emissions. Affluent cities includes Beijing, Tianjin and Jiangsu reduce carbon emissions by interprovincial trade. The trade within provinces located in the fourth quadrant reduced provincial emissions but increased national emissions. For example, Zhejiang imports a great number of products in heavy industry from the less developed regions. Similarly, US decrease domestic emissions by consuming carbon-intensive products manufactured in other countries while global emissions is increased (Zhang et al., 2017).

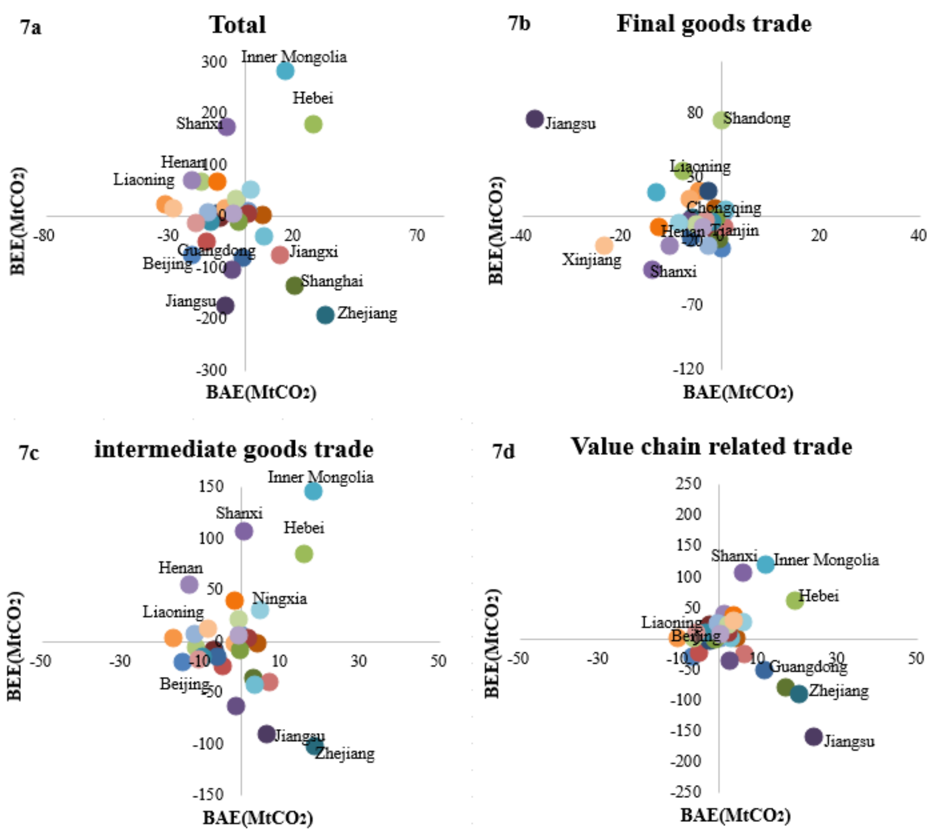

Fig. 7. Environmental effects of interprovincial trade (7a), final goods trade (7b), intermediate goods trade (7c) and value chain related trade (7d) on national and provincial carbon emissions ($MtCO_2$)

Attention needs to be paid to the regions located in the first quadrant of Fig. 7 where these provinces contribute to a large amount of carbon emissions induced by trade patterns both locally and nationally. In six provinces, interprovincial trade increases carbon emissions of itself as well as national emissions, i.e. Hebei, Inner Mongolia, Guangxi, Fujian, Ningxia and Anhui. Therefore, these six provinces play a vital role in achieving the national target of carbon reduction. From the perspective of trade patterns, Hubei, Shandong and Fujian are crucial provinces in final goods trade. Inner Mongolia, Hebei, Guangxi and Ningxia are critical provinces in intermediate goods trade. For value chain related trade, focus should be placed on nine provinces, such as Hebei, Shanxi. Nevertheless, the effects of the same provinces on carbon emissions varied according to trade patterns. For example, as the largest net carbon exporter, Inner Mongolia increases the most carbon emissions of China by 42Mt especially through the trade of intermediate goods and value chain. On the contrary, Hebei alleviates this situation in the trade of final goods.

Similarly, attention should be paid to the high-carbon-emission sectors of 11 provinces in the first quadrant in Fig. 7, such as energy sector, non-metal and metal products and mineral products (Fig. 8.). For Inner Mongolia and Ningxia, carbon embodied in energy sectors contributes up to 74% of the total emissions embodied in trade. For Hebei, Guangxi and Hubei, non-metal and metal sectors should decrease its carbon emissions because 36-58% of these provinces' total emissions are from this sector. For Shanxi and Xinjiang, all of them are rich in mining products. Indeed, mining products should be given priority for those provinces with carbon reduction targets.

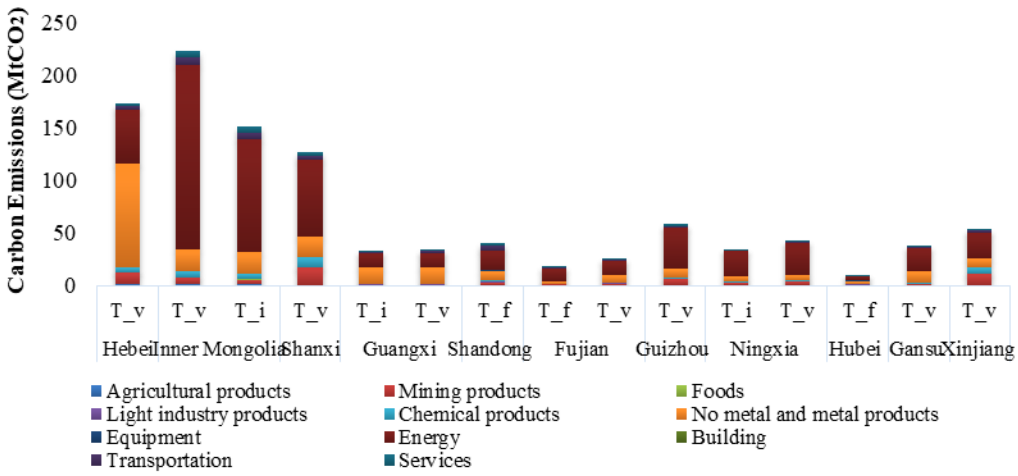

Fig. 8. Carbon emissions embodied in sectors of trade of the first type provinces

Note: the first type provinces: 15 provinces located in the first quadrant of Figure 8 contribute a large amount of carbon emissions induced by trade patterns to China and their own. T_f indicates trade in final products. T_i indicates trade in intermediate products for the last stage of production. T_v indicates the value chain related trade.

4. Discussion

This section compares the results of this paper with those of previous studies. Comparison on carbon emissions embodied in interregional trade is made with Mi et al.'s (2017) paper. In addition, comparisons are made on the effects of interregional trade on national or regional carbon emissions with Zhang et al.'s (2012) study, Zhang et al.' 2014 study and López et al.'s (2018) paper.

We find some similar results when comparing with previous studies on the carbon transfer within China and the avoided embodied emissions.

Firstly, we adopt the same region classification of Mi et al.'s (2017) study and compare interregional carbon transfer within China in 2012. As shown in Fig. S.1, our results are similar with those of Mi et al.'s study, both of which indicate that the Northwest region had the largest carbon outflows, Central and Central Coast regions had the largest carbon inflows. The developed regions, such as the eastern coastal provinces, outsource huge amount of carbon emissions related to goods and services to the less developed Central and Western China.

Secondly, we compare the results about the effects of trade on national emissions with previous studies. The results are shown in Table 2. It can be observed there is no significant difference of the balance of avoided emissions between results of this paper and that of previous studies. The differences of carbon emissions embodied in national or regional export may be due to the difference on calculation results. For example, the MRIO tables of Zhang et al. (2014) are from the Development Research

Center of the State Council, P.R.C. (Li et al., 2010; Xu and Li, 2008). MRIO tables employed in this study are constructed by the Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences (Liu et al., 2012; Liu et al., 2014). Besides, the different carbon emissions calculation may also lead to the differ in embodied emissions in exports. Zhang et al. (2014) calculated the CO_2 emissions based on the emissions factors provided in IPCC (2006). While Shan et al. (2016, 2017) pointed that the emission factors recommended by the IPCC are frequently higher than the real emissions factors. In our study, we adopted the emission factors provided by CEADs (Shan et al., 2017). We considered different oxygenation efficiency for fossil fuels burnt in different sectors, as the combustion technology level of sectors are different in China. While Zhang et al. (2014) assumed that all the carbons in the fuel are completely combusted and transferred into the carbon dioxide form. Thus the values of embodied emissions in exports in this paper are lower than that of Zhang et al. (2014).

Table 2 Comparison with previous studies (million tons CO_2)

	Carbon emissions embodied in exports	Balance of avoided emissions
Zhang (2012)	1751 (2007, national)	712 (2007, national)
Zhang et al. (2014)	6226 (2007, regional)	-119 (2007, regional)
Lopez et al. (2018)	1987 (2009, national)	1228 (2009, national)
This paper	2967 (2007, regional)	-208 (2007, regional)
	3426 (2010, regional)	247 (2010, regional)
	4010 (2012, regional)	-229 (2012, regional)

Some differences between findings of this study and those of existing studies are also highlighted, which mainly due to the impact of production fragmentation. For example, the total carbon emissions embodied in interregional trade of this paper is 18% higher than that of Mi et al.'s paper. Part of the reason is that the estimation of export could be greatly affected by different approaches due to interregional feedback effects (Su and Ang, 2014). Mi et al. (2017) calculated the embodied carbon emissions in interregional trade by the MRIO approach which is suitable for calculating the emissions embodied by the final consumption. While this approach could not identify the emissions induced by different trade patterns and not recognize what's the spillover effects of interregional trade on national carbon emissions. Without concerns on carbon transfer among regions, it would be difficult to identify the responsibility for carbon reduction except to distinguish the final goods trade from the intermediate goods trade. Therefore, this paper calculate the interregional export by EEBT approach which would allocate some parts of the national carbon emissions to interregional trade (Su and Ang, 2011) and identify the impacts of different trade patterns between regions on national carbon emissions which is one of the contributions of this paper.

5. Conclusions and policy implications

At the 2015 Paris Summit, China committed to decrease carbon intensity by 60% - 65% in 2030 as compared to that in 2005. To achieve this target, carbon emissions induced by trade should be focused on, which take accounts for 50% of national carbon emissions. Over recent decades, interregional trade within China has evolved with the growing fragmentation of production network. We enrich the existing studies by examining the carbon transfer within China from the perspective of production fragmentation with the MRIO analysis. The main conclusions of this study are summarized below.

First, production fragmentation shape the CO_2 induced by different trade patterns. With the growth of inter-provincial trade volume, carbon emissions embodied in inter-provincial trade grew by 24% from 2007 to 2012. Among different trade patterns, carbon emissions embodied in value chain related trade kept accounting for the largest proportion and increased by 9% for these years. Provincial decompositions show that provinces and sectors with large amount of embodied carbon emissions mainly concentrated in inland provinces with rich resources and the carbon-intensive sectors. There are significant differences in the share of emissions induced by different economic activities, which is closely related to its position in production fragmentation. With the rapid economic growth and development of production fragmentation, trade scale will keep increase and production chain will be more complicated in the future. This highlights carbon emissions induced by value chain related trade should be given attention and the responsibility of carbon reduction should be shared with all participants in the value chain instead of the producer of final products. In order to alleviate the environmental effects of domestic trade, it is necessary to monitor and control the CO_2 emitted in each production processes throughout the supply chain. Green supply-chain management (GSCM) is one of the options, which is committed to minimize the environmental impacts of a product throughout the lifecycle by greener design, recyclable materials, cleaner production, etc. (Ahi and Searcy, 2015). It is still at the early stage in China. The concept of

GSCM could be introduced into carbon reduction. The responsibility of carbon reduction can be allocated to all participators in the supply chain, and the whole process can be monitored from production to consumption.

Second, all stakeholders in the value chain should take responsibility for carbon reduction. From the perspective of carbon transfer, most inland and less developed regions, such as Inner Mongolia, Hebei and Shanxi, are typically net exporters of embodied carbon emissions. Beijing, Tianjin and Yangtze River Delta are net importers of embodied emissions who are also the relatively developed parts and have advantages in economic and technology. Carbon transfer by bilateral trade within China is uneven in geography, which mainly concentrates in North China and southern coastal areas. Based on the prior studies on the consumption-based responsibility of carbon reduction (Jiang et al., 2015), we inform that the provinces involved in the interregional trade, especially in the value chain related trade (e.g. exporters, importers, processors), and the final users, should bear the responsibility of carbon reduction throughout the country. For example, to realize the Paris Agreement's Chinese commitments, the government could use the percentage of carbon emissions induced by value chain related trade of each province as part of the basis for allocation of national carbon responsibility. Similar with the theory of responsibility principle on climate change, the added-value in supply chain, the environmental impacts, and all stakeholders should be involved in the compensation framework.

Third, it is crucial to alleviate the negative effect on national carbon emissions induced by production fragmentation. This study evaluates the effect of interregional trade on national carbon emissions. In general, inter-provincial trade within China generate national carbon emissions saving by 114 Mt in 2012. Trade in final products and trade in intermediate goods products contributes a reduction by 182Mt and 39Mt, respectively, because downstream production gradually shifted to provinces with cleaner production technology and lower carbon intensities. While the value chain related trade contribute a growth to national carbon emissions. This is because the low-value-added process of productions are outsourced to the provinces with higher carbon intensity. According to results of this study, trades between different provinces have different effects on national and provincial carbon emissions. Based on their effects, we divided the provinces into four types. The Type I provinces whose trade increase carbon emissions of China and itself should be paid special attention, such as Inner Mongolia. Due to the backward technology and carbon-intensive industry structure, these provinces supply the low-value-added and high-carbon products with importers in the supply chain. Governments should invest more in R&D in the Type I provinces and promote the development of clean technology and renewable energy, such as the solar power. Similarly, the Type IV provinces may be the importer of Type I provinces whose trade activities drop the local emissions while raise the national carbon emissions. For these two types of provinces, government could propose market-oriented policies by means of enforcement or incentive and achieve shared responsibly of climate change. Carbon tax is an economic means to internalize the social costs of environmental pollution and ecological destruction into production costs and market prices, and then distribute environmental resources through market mechanism. Producers can pass on carbon taxes to importers by raising product prices and realize shared responsibility. For Type II and Type III provinces, the carbon emissions induced by trade haven't stimulated the growth of national carbon emissions, which should not be controlled by the government, although the domestic trade increase the carbon emissions of Type II provinces.

There are some limitations of this study which is similar to other papers utilizing MRIO approach. First, due to the lack of product specificity within sectors, the aggregation error may significantly affect our estimates of the carbon transfer among provinces. Since the carbon emissions within a specific sector was assumed homogeneity, the distinct differences within different industrial processes are not taken into consideration. Second, this study didn't not distinguish production process for final products from that for intermediate products. This is because the input-output model assumed the output of each sector was homogeneous, which may influence estimates on the carbon transfer derived from different trade patterns.

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Supporting Information. Additional details on approaches, figures and tables**.**

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