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RESEARCH ARTICLE

Structural decomposition analysis of embodied carbon in trade in the middle reaches of the Yangtze River

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Abstract
The middle reaches of the Yangtze River are the first demonstration zone for low-carbon urbanization in the midwest regions of China, and the division of carbon emission reduction responsibility is an important aspect of construction of ecological civilization. In this paper, the embodied carbon emissions in trade are estimated by using an input–output model in the middle reaches of the Yangtze River, and then a structural decomposition analysis (SDA) model is further applied to conduct decomposition analysis on factors of embodied carbon changes. Our primary findings show the following: (1) Production-based CO_2 emissions from Hubei and Hunan are higher than consumption-based CO_2 emissions. There are situations in Jiangxi and Anhui where production-based CO_2 emissions are both higher and lower than consumption-based CO_2 emissions. However, inter-regional trade implied carbon is dominated by net inflows. Moreover, the inter-regional embodied carbon emissions in trade mainly flow out to relatively developed regions, such as Jiangsu and Shanghai. The inflow of embodied carbon in trade comes mainly from relatively backward economic development areas, such as Shaanxi and Inner Mongolia. (2) From the perspective of industry, industries in Jiangxi and Anhui are dominated by net inflow, whereas industries in Hunan and Hubei are dominated by net outflow. Meanwhile, industry in the middle reaches of the Yangtze River displays a high carbon-locked phenomenon. Specifically, the high carbon-locked outflow industries are mainly concentrated in the transportation and warehousing industry, agriculture, and the chemical industry, and the outflow provinces flow out mainly to Jiangsu, Guangdong, and other economically developed regions; high carbon-locked inflows are concentrated in metal smelting and rolling processing, food manufacturing and tobacco processing, and construction, and the provinces are mainly Hebei, Henan, and Inner Mongolia, where economic development is lacking. (3) Furthermore, the results of SDA decomposition indicate that scale effect is generally the most important factor leading to embodied carbon outflow. Meanwhile, the energy carbon emission effect, the energy intensity effect, and the structural effect are important factors—the inter-industry association effect mainly promotes the embodied carbon outflow. Consequently, based on the distinction between production and consumer responsibility, and from the perspective of scale effect and structural effect, the related policy suggests that consumers should be held responsible.

Keywords Input–output model · Embodied carbon emissions in trade · SDA model · Responsibility for reducing emission

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Introduction

Addressing climate change has become a common environmental issue throughout the world. China has taken climate change issues extremely seriously, as it is one of the countries mainly responsible for climate change (Ge et al. 2000; Ge 2009; Gao et al. 2012; Ge et al. 2015). For this reason, at the Climate Change Conference in Paris, China clearly stated that it plans to achieve peak carbon emissions in 2030 and will strive to peak as soon as possible. In fact, the time and level of the carbon peak depend on the coming transformation of the regional development pattern and national policy orientation (Cai et al. 2015; He et al. 2016). However, in the rapid development process of regional integration, regional trade is bound to be accompanied by the separation of geographical space between the producers and the consumers of products, which may lead to inter-regional transfer of carbon emissions (Chen et al. 2016). The obvious reason for consideration of the characteristics and impacts of the embodied carbon characteristics of regional trade is to develop a responsibility sharing mechanism for emission reduction, which is a key issue for regional cooperation emission reduction.

Currently, most studies on embodied carbon emissions in trade and related issues of emission reduction responsibility are conducted mainly in terms of the following three aspects: first, studies regarding calculating carbon emissions and carbon emission transfer among different regions of China, as well as the spatial transfer characteristics of carbon emissions, all of which are based on the "production–consumption" responsibility theory (Zhang et al. 2011; Feng et al. 2013; Vause et al. 2013; Peng et al. 2015; Zhong et al. 2018); second, studies of embodied carbon in trade and emission reduction of this carbon at either a single province or a national level (Chen et al. 2013; Zhang et al. 2014; Huang et al. 2015; Zhong et al. 2017); third, discussions on the trend of evolution of industrial structure and the potential of emission reduction policies (Qi and Zhang 2013; Zhang and Tang 2015; Wu et al. 2015a, b).

When studying the driving factors of trade embodied carbon change, scholars tend to favor two methods: index decomposition analysis (IDA) and structural decomposition analysis (SDA). For example, Peters et al. (2007) used the SDA model to analyze the factors affecting China's carbon emissions' growth in 1992–2002, and their findings indicated that economic structure, technology level, and urban resident fees have a significant impact on growth of carbon emissions. Minx et al. (2011) expanded Peters' early research on China's carbon emissions, further revealing that technological advances in the production sector in 2002–2007 largely offset the growth in carbon emissions caused by the final demand sector. Guan et al. (2009) used the IO–SDA model to determine, from the final demand perspective, that urban residents' consumption, fixed asset investment, and export trade had a significant effect on China's carbon emissions' growth in 2002–2007. Clearly, the SDA model has been used frequently to study how changes in individual variables affect the growth of embodied carbon emissions from trade outflows (Cansino et al. 2016; Su and Ang 2017; Mi et al. 2017; Román-Collado and Colinet 2018; Sun et al. 2018). However, it should be pointed out that the IDA model studies the direct effects of changes in economic, structural, and population factors on carbon emissions based on the form of data aggregation (Ang 1995), whereas the SDA model is based on classical input–output theory (Rose and Casler 1996; Casler and Rose 1998), which compensates for the inability of the IDA model to analyze the indirect impact of changes in the final demand sector on carbon emissions, and the data are more comprehensive and analytically detailed (Peters et al. 2007; Minx et al. 2011; Su et al. 2013; Su and Ang 2012; Kim et al. 2015; Su et al. 2017). For this reason, the SDA model has become a mainstream research method used by domestic and foreign scholars to analyze economic, energy, and carbon emissions' issues.

Also, a number of important studies have been conducted to explore the reason for transferring CO_2 emissions. For instance, the factors affecting CO_2 emissions in China were analyzed based on the STIRPAT model, and the results showed that per capita GDP growth is the most important factor contributing to the increase of CO_2 emissions (Li et al. 2011). Other scholars have adopted the LMDI decomposition method, which has shown that the population-scale effect has a large positive impact on regional carbon emissions. The positive effect of economic development on carbon emissions is weaker in economically developed regions than in other regions. The energy intensity effect has a strong inhibitory effect on carbon emissions in areas with active economic restructuring. The effects of energy structure effects on carbon emissions are highly volatile (Deng et al. 2014). Other examples have adopted the LMDI decomposition method to decompose China's carbon emissions from 1994 to 2008. From the perspective of industrial structure, the contribution of the six major industrial sectors to carbon emissions has been explored, and the impacts of energy structure, energy intensity, industrial structure, and total output value on carbon emissions have been analyzed (Lu et al. 2013). Based on GTAP8, a MRIO model was built to analyze the factors influencing the total embodied carbon emissions in China's exports to the EU from 2004 to 2007. The results show that the expansion of export scale is the main reason for embodied carbon emissions' increase in China. Technological progression has played a role in reducing these emissions, and structural effects have generally contributed to their increase to some extent (Pang and Zhang 2014). Obviously, combining carbon emission factors has had strong practical guiding significance for the division of emission reduction responsibilities. Although the above results have made a very meaningful contribution, there is still space for further study. For instance, firstly, in the study of regional carbon emissions and related issues, the study of individual provinces and regions has matured (Wu et al. 2015a, b; Wang et al. 2016; Huang et al. 2015; Wang et al. 2013; Xi et al. 2011), but there is a relative lacking of research on multi-regions. Therefore, this paper focuses on the middle reaches of the Yangtze River to complement the carbon emissions' research at the multi-regional level. Secondly, SDA is an effective method for exploring the driving factors. It is commonly utilized to find out how changes in various variables affect the growth of embodied carbon in trade outflows, that is, the contribution of each independent variable to dependent variables (Wang et al. 2012; Xu and Dietzenbacher 2014; Gu and Lv 2016; Wang et al. 2017). However, most of the previous research on driving factors has been limited to three to four variables; therefore, to explore the deeper reasons behind the embodied carbon in trade, this paper will further explore the issue on the basis of former factor decomposition.

Applying an input–output model and an SDA model, this paper chooses the middle reaches of the Yangtze River as its research object to explore the following two important issues: First, throughout the whole country, the embodied carbon emissions in trade are from either production or consumption in the middle reaches of the Yangtze River, and we try to identify the main industries and other regional of embodied carbon flowing to the middle reaches of the Yangtze River. Second, at the policy level of emission reduction responsibility, this paper gives the definition of emission reduction responsibility between production and consumption. Meanwhile, the result of the research provides reliable evidence for the country's scientific emission reduction policy.

Methodology and data

Case study

With the rapid development of the regional economy, the demand for external energy in the middle reaches of the Yangtze River is expanding, and the carbon emissions implied in energy will keep growing. In the context of rapid regional economic development, the total energy consumption in the middle reaches of the Yangtze River increased from 365.64 million tons of standard coal in 2007 to 530.10 million tons of standard coal in 2012, with an average annual growth rate of 7.71% (CESY 2015). Compounding matters, the region relies heavily on external energy consumption, among which the energy demand transferred from other regions of China after conversion into standard coal increased from 242.66 million tons of standard coal in 2007 to 339.10 million tons of standard coal in 2012, with an average annual growth rate of approximately 6.92% (CSY 2015). Obviously, as the regional energy demand continues to increase, the carbon emissions implicit in energy consumption will also increase. In addition, Huang et al. (2018) have also shown that the Yangtze River economic belt has a high degree of carbon emissions, of which the carbon emissions in the middle reaches of the Yangtze River are the fastest, and it is predicted that the central region will become the main source of carbon emissions in 2030. It can be seen that the carbon emission reduction situation in the middle reaches of the Yangtze River is very serious.

Also, the middle reaches of the Yangtze River play a role in linking the upstream and the downstream reaches and also play a significant role in the growth of carbon emissions in the Yangtze River economic belt. To sum up, it is of great practical significance to conduct relevant research on embodied carbon in trade at the middle reaches of the Yangtze River.

Methodology

Input–output model

Multi-region input–output tables can better illustrate the complex industry linkages between different regions and different industry sectors; therefore, many scholars prefer to use them to study issues related to carbon emissions on the Chinese scale (Su and Ang 2014; Chen et al. 2015; Zhang et al. 2016; Cheng et al. 2014; Li et al. 2017, 2018; Chen et al. 2018; Wu et al. 2018). Based on the knowledge of macroeconomics combined with matrix algebra, the input–output table is further expressed mathematically as:

$$X = (I-A)^{-1}\, Y \tag{1}$$

where X is the total output vector of the sectors, Y is the final demand vector, A is the direct consumption coefficient matrix, and I is the identity matrix which is of the same order as A. $(I-A)^{-1}$ is the Leontief inverse matrix. To improve research on CO_2 emissions embodied in trade outflow, the direct carbon emission coefficient is introduced on the basis of the above formula, and the new formula can be expressed as:

$$\mathrm{EC} = E\,(I-A)^{-1}\, Y \tag{2}$$

where EC is the total carbon emissions, E is the direct carbon emission coefficient of the industry sector, and Y can be further decomposed to:

$$\mathrm{EC} = E\,(I-A)^{-1}\left(Y_{\mathrm{ii}} + Y_{\mathrm{ij}}\right) \tag{3}$$

Y_{ii} indicates the goods used for production and consumption in the region. Conversely, Y_{ij} indicates the demand for trade to other regions.

SDA model

The SDA model has various estimation methods, with the weighted average method being relatively mature in terms of theory. Due to the large degree of computation involved and difficulty of operation, this method is rarely used. However, the bipolar decomposition method can avoid the above shortcomings, while obtaining a similar solution to that obtained using the weighted average method. In this paper, the bipolar decomposition method is used to conduct structural decomposition analysis (Du and Zhang 2012; Zhao et al. 2014; Zhao and Liu 2015; Jiang 2016).

To measure the variable factors affecting CO_2 emissions embodied in trade at the two periods, the SDA bipolar decomposition method is implemented and expanded based on Eq. (2); it can be measured as:

$$\mathrm{EC} = C\,M\,(I - A)^{-1}F\,S \tag{4}$$

With the above formula, C is the ratio of CO_2 emissions to energy consumption, that is, the energy carbon emission effect that reflects how many units of CO_2 can be released by one unit of energy, in which CO_2 emission is the product of energy-related data. M represents the product of energy consumption and the reciprocal of the total output of sectors, namely the energy intensity effect, which reflects the energy consumed by per unit GDP; $(I-A)^{-1}$ represents the Leontief inverse matrix and reflects the degree of association between industries, namely the inter-industry correlation effect, which is recorded as L; F is the total outflow from one province to another, called the scale effect; and S is the ratio of the export value of an industrial sector from one province to another province to F, called the structure effect. On the basis of Eq. (4), the bipolar decomposition method in SDA is used to conduct structural analysis and decomposition of ΔEC. The subscripts 0 and 1 represent the base period and the reporting period, respectively. If Eq. (4) is decomposed from the base period (0 period), it can be formulated as:

$$\begin{aligned}\Delta\mathrm{EC} &= \mathrm{EC}_1 - \mathrm{EC}_0 = C_1M_1L_1F_1S_1 - C_0M_0L_0F_0S_0\\ &= \Delta CM_0L_0F_0S_0 + C_1\Delta ML_0F_0S_0 + C_1M_1\Delta LF_0S_0\\ &\quad + C_1M_1L_1\Delta FS_0 + C_1M_1L_1F_1\Delta S\end{aligned} \tag{5}$$

If it is decomposed from reporting period (1 period), it can be formulated as:

$$\begin{aligned}\Delta\mathrm{EC} &= \mathrm{EC}_1 - \mathrm{EC}_0 = C_1M_1L_1F_1S_1 - C_0M_0L_0F_0S_0\\ &= \Delta CM_1L_1F_1S_1 + C_0\Delta ML_1F_1S_1 + C_0M_0\Delta LF_1S_1\\ &\quad + C_0M_0L_0\Delta FS_1 + C_0M_0L_0F_0\Delta S\end{aligned} \tag{6}$$

By calculating the arithmetic mean of the 0 and 1 periods, it can be obtained:

$$\begin{aligned}\Delta\mathrm{EC} &= 1/2(\Delta CM_0L_0F_0S_0 + \Delta CM_1L_1F_1S_1)\\ &\quad + 1/2(C_1\Delta ML_0F_0S_0 + C_0\Delta ML_1F_1S_1)\\ &\quad + 1/2(C_1M_1\Delta LF_0S_0 + C_0M_0\Delta LF_1S_1)\\ &\quad + 1/2(C_1M_1L_1\Delta FS_0 + C_0M_0L_0\Delta FS_1)\\ &\quad + 1/2(C_1M_1L_1F_1\Delta S + C_0M_0L_0\Delta FS_1)\end{aligned} \tag{7}$$

The above equality can be further written as:

$$\begin{aligned}f(\Delta\mathrm{EC}) &= f(\Delta C) + f(\Delta M) + f(\Delta L) + f(\Delta F)\\ &\quad + f(\Delta S)\end{aligned} \tag{8}$$

Equation (8) consists of five items that represent the influence of five independent variables on the CO_2 emissions embodied in trade outflow (see Table 1).

Data

Two aspects of data are required when estimating the embodied carbon in trade between the middle reaches of Yangtze River and other regions, i.e., data that reflect the multi-regional input–output data associated with other regions in the middle reaches of the Yangtze River, and the direct carbon emission coefficient of each sector.

1. Input–output table: To meet the requirements, this paper adopts China's multi-regional input–output table.

Table 1 Calculation formula for driving factors of the outflow of embodied carbon

Driving factor	Contribution (f)	Expansion formula of contribution
Energy carbon emission effect	$f(\Delta C)$	$1/2(\Delta CM_0L_0F_0S_0 + \Delta CM_1L_1F_1S_1)$
Energy intensity effect	$f(\Delta M)$	$1/2(C_1\Delta ML_0F_0S_0 + C_0\Delta ML_1F_1S_1)$
Inter-industry correlation effect	$f(\Delta L)$	$1/2(C_1M_1\Delta LF_0S_0 + C_0M_0\Delta LF_1S_1)$
Scale effect	$f(\Delta F)$	$1/2(C_1M_1L_1\Delta FS_0 + C_0M_0L_0\Delta FS_1)$
Structure effect	$f(\Delta S)$	$1/2(C_1M_1L_1F_1\Delta S + C_0M_0L_0\Delta FS_1)$

Table 2 Classification of industrial sectors

ID	Industries	ID	Industries
1	Agriculture	16	General and special equipment manufacturing industry
2	Coal mining and washing industry	17	Transportation equipment manufacturing industry
3	Oil and gas extraction industry	18	Electrical machinery and the equipment manufacturing industry
4	Metal mining and dressing industry	19	Communications equipment, computers, and Other electronic equipment manufacturing industry
5	Nonmetallic minerals and other minerals' mining and selection industry	20	Instrument, cultural, and office machinery industry
6	Food manufacturing and tobacco processing industry	21	Other manufacturing industry
7	Textile industry	22	Production and supply of electric power and hot power industry
8	Textiles, clothing, shoes, hats, leather, feather and its products industry	23	Production and supply of gas and water industry
9	Wood processing and furniture manufacturing industry	24	Construction industry
10	Paper printing, cultural and educational sports products manufacturing industry	25	Transportation and warehousing industry
11	Petroleum processing, coking, and nuclear fuel processing industry	26	Wholesale and retail industry
12	Chemical industry	27	Lodging and catering industry
13	Nonmetallic mineral products industry	28	Leasing and business services industry
14	Metal smelting and rolling processing industry	29	Research and experimental development industry
15	Metal product industry	30	Other services industry

Since the latest available input–output table is from 2012, this study chooses data from 2007, 2010, and 2012 to explore the carbon emissions in the middle reaches of the Yangtze River. The obtained input–output table was treated as follows: First, regarding the division of industry sectors, see Table 2. It is 30 industry sectors in 30 provinces and regions of China (except Tibet, Taiwan and Hong Kong and Macau). In addition, to eliminate the effect of inflation, the study was calibrated for 2010 and 2012 on the basis of 2007, to ensure the comparability of data, and the corresponding data were derived from the China Statistical Yearbook.

2. Direct carbon emission coefficient: First, based on the China Energy Statistics Yearbooks for 2008, 2011, and 2013, the energy data of 2007, 2010, and 2012 (including coal, coke, gasoline, kerosene, diesel, fuel oil, and natural gas) are applied in this article, according to the final energy consumption in various industries of the energy balance sheet, and the energy consumption of 30 sectors in different provinces and regions is obtained. Secondly, combined with the energy emission factors provided by IPCC (2006), the carbon emissions from different sectors of the provinces and regions can be obtained; this determines the direct carbon emission coefficient, and then the direct carbon emission coefficients corresponding to different departments in different provinces and regions are obtained.

Results and discussions

CO_2 emissions based on production–consumption model

The national multi-region input–output table can be built on the basis of Eqs. (1) and (2), after which it is calculated according to Eq. (3). Table 3 gives the production-based and consumption-based CO_2 emissions of the middle reaches of the Yangtze River in 2007, 2010, and 2012.

Table 3 shows that, in 2007, 2010, and 2012, the production-based and consumption-based CO_2 emissions of the middle reaches of the Yangtze River are divided into two categories, as shown in Table 3. One category is Hubei and Hunan, where the production-based CO_2 emissions are higher than the consumption-based CO_2 emissions. In 2007 and 2012, production-based and consumption-based CO_2 emissions of the two provinces are similar; this is due to the fact that there is little difference between the carbon content of products and services for output and the demand for energy-intensive products in other provinces. It is further discovered that the production-based CO_2 emissions in 2010 are approximately two times the consumption-based CO_2 emissions. The reason may be that these two provinces have some demand for energy-intensive products from other provinces, but the demand is much less than that for those exported to other provinces. This may be part of the demand for energy-intensive products in the two provinces, but the demand is far less than

Table 3 CO_2 emissions of "production–consumption" based (unit: Mt CO_2)

Year	Jiangxi province		Hunan province		Hubei province		Anhui province	
	Production-based emissions	Consumption-based emissions	Production-based emissions	Consumption-based emissions	Production-based emissions	Consumption-based emissions	Production-based emissions	Consumption-based emissions
2007	40.08	42.97	96.97	92.63	121.09	116.40	35.27	34.40
2010	60.94	46.30	102.22	52.83	142.43	71.88	57.88	31.71
2012	73.16	76.76	128.80	126.61	201.48	200.15	65.98	71.82

for either the products or the services exported to other provinces.

The other category is Jiangxi and Anhui, where, in 2007, 2010, and 2012, the production-based CO_2 emissions are sometimes higher and sometimes lower than the consumption-based CO_2 emissions. The reason may be that the two provinces are economically underdeveloped areas, and the structure of the industry is inadequate. Therefore, there are some differences in the transfer of either goods or services to other regions through inter-regional trade in different years. In general, production-based CO_2 emissions of the middle reaches of the Yangtze River in 2007 are higher than consumption-based CO_2 emissions. Therefore, under the production responsibility system, the middle reaches of the Yangtze River indirectly undertook some emissions' responsibilities for other provinces.

Comparative analysis of embodied carbon in trade at the middle reaches of the Yangtze River

The total outflow, inflow, and net outflow of embodied carbon in trade at the middle reaches of the Yangtze River in 2007, 2010, and 2012 can be obtained according to the multi-region input–output table. The results are shown in Table 4.

Embodied carbon in the middle reaches of the Yangtze River in 2007, 2010, and 2012 can be divided roughly into two categories. The first category of the embodied carbon in trade is Hubei and Hunan, where a positive net outflow is always present. The outflow of embodied carbon in trade from these provinces shows a trend of reducing after increasing. Although the outflow of Hunan increased by 2.35 Mt CO_2 from 2010 to 2012, the relative value of the inflow was larger than that of the outflow, which resulted in the net output showing a decreasing trend in Hunan. On the whole, Hunan and Hubei are noted as being positive net outflow areas; this may be due to the fact that these two regions export mainly high-energy-consuming goods or services, such as energy and chemicals, and input mainly green and low-carbon products, such as deep processing products.

The second type of embodied carbon in trade is Jiangxi and Anhui with net inflow. Embodied carbon in Jiangxi and Anhui outflows to other parts of the country has shown an increasing trend. In 2012, the inflow of Anhui was 21.16 Mt CO_2, approximately three times that of 2010, and its relative increase of inflow was far greater than the relative increase of outflow, which made Anhui becomes a net inflow area in 2012. Jiangxi has always been in a state of net inflow. Overall, Jiangxi and Anhui maintain net inflow, perhaps because the two provinces are both economically underdeveloped areas, and the structure of the industry should be improved. To meet local consumption demand, it is necessary to transfer goods or services from other areas through inter-regional trade. To some extent, the responsibility for reducing the production-based emissions is less than that for reducing the consumption-based emissions.

Furthermore, the flow direction of embodied carbon in trade for major provinces has also been investigated to enrich the study on trade embodied carbon from the regional perspective here. However, due to space limitations, this section selects for research six provinces with higher outflows in the middle reaches of the Yangtze River and six provinces in other provinces that flow into the middle reaches of the Yangtze River. The results are shown in Table 5. The inflow of

Table 4 Comparison of embodied carbon in trade in the middle reaches of the Yangtze River (unit: Mt CO_2)

Year	Anhui province			Jiangxi province			Hubei province			Hunan province		
	Outflow	Inflow	Net outflow	Outflow	Inflow	Net outflow	Outflow	Inflow	Net outflow	Outflow	Inflow	Net outflow
2007	6.22	5.34	0.87	1.46	4.35	−2.89	7.83	2.98	4.84	6.97	2.64	4.33
2010	7.55	6.84	0.71	1.95	3.97	−2.02	9.84	3.34	6.50	6.25	3.27	2.99
2012	15.26	21.16	−5.89	4.53	8.17	−3.64	2.90	1.45	1.45	8.60	6.47	2.13

If net outflow is not negative, it is defined as net inflow

Table 5 Main areas of trade embodied carbon inflow and outflow in the middle reaches of the Yangtze River (unit: Mt CO_2)

Province	Year											
	2007				2010				2012			
	Outflow		Inflow		Outflow		Inflow		Outflow		Inflow	
	Province	E	Province	I	Province	E	Province	I	Province	E	Province	I
Anhui province	Jiangsu	0.76	Hebei	0.73	Jiangsu	0.97	Hebei	1.30	Jiangsu	4.55	Shanghai	3.23
	Zhejiang	0.73	Shaanxi	0.46	Tianjin	0.71	Shaanxi	0.44	Jiangxi	1.91	Inner Mongolia	2.70
	Shanghai	0.59	Inner Mongolia	0.32	Shanghai	0.67	Inner Mongolia	0.41	Shanghai	1.46	Jiangsu	2.21
	Tianjin	0.58	Jilin	0.28	Zhejiang	0.55	Shandong	0.35	Henan	0.89	Hebei	1.30
	Hebei	0.42	Hunan	0.25	Henan	0.49	Shanxi	0.31	Zhejiang	0.89	Henan	1.10
	Beijing	0.39	Jiangsu	0.25	Beijing	0.49	Xinjiang	0.30	Shandong	0.86	Shanxi	1.08
Jiangxi province	Guangdong	0.32	Hebei	0.38	Guangdong	0.10	Shanghai	0.40	Jiangsu	0.69	Anhui	1.91
	Zhejiang	0.21	Shanghai	0.37	Zhejiang	0.47	Hebei	0.39	Anhui	0.55	Shanghai	0.78
	Shanghai	0.13	Beijing	0.37	Shanghai	0.31	Guizhou	0.31	Shandong	0.51	Inner Mongolia	0.74
	Fujian	0.13	Guizhou	0.35	Fujian	0.15	Shaanxi	0.30	Zhejiang	0.46	Hebei	0.43
	Jiangsu	0.10	Inner Mongolia	0.33	Jiangsu	0.15	Inner Mongolia	0.25	Guangdong	0.37	Henan	0.42
	Anhui	0.06	Shaanxi	0.29	Anhui	0.15	Hubei	0.25	Shanghai	0.36	Shaanxi	0.40
Hubei province	Tianjin	1.12	Yunnan	0.28	Tianjin	1.34	Shanxi	0.39	Anhui	0.31	Shanxi	0.45
	Guangdong	0.86	Hebei	0.28	Guangdong	1.03	Hebei	0.37	Henan	0.27	Inner Mongolia	0.11
	Jiangsu	0.62	Inner Mongolia	0.21	Jiangsu	0.76	Yunnan	0.30	Jiangsu	0.26	Guizhou	0.10
	Hebei	0.53	Shaanxi	0.19	Beijing	0.70	Inner Mongolia	0.22	Zhejiang	0.24	Henan	0.10
	Fujian	0.52	Shanxi	0.17	Shanghai	0.65	Shaanxi	0.19	Hunan	0.20	Shaanxi	0.10
	Beijing	0.45	Xinjiang	0.17	Fujian	0.55	Shanghai	0.19	Guangdong	0.19	Hunan	0.08
Hunan province	Guangdong	1.79	Yunnan	0.23	Guangdong	1.35	Shaanxi	0.34	Guangdong	0.93	Inner Mongolia	0.49
	Zhejiang	0.72	Shaanxi	0.20	Zhejiang	0.47	Yunnan	0.24	Jiangsu	0.74	Chongqing	0.45
	Shanghai	0.43	Guizhou	0.20	Guangxi	0.46	Hebei	0.24	Henan	0.71	Shanghai	0.41
	Guangxi	0.36	Hebei	0.18	Shanghai	0.33	Guizhou	0.21	Hebei	0.59	Shanxi	0.41
	Jiangsu	0.29	Guangdong	0.16	Jiangsu	0.27	Chongqing	0.17	Anhui	0.58	Guizhou	0.37
	Hebei	0.28	Henan	0.14	Inner Mongolia	0.27	Henan	0.16	Shandong	0.58	Yunnan	0.37

E, outflow; *I*, inflow

embodied carbon in the inter-regional trade between Jiangxi and Anhui is mainly from Hebei, Inner Mongolia, and Shaanxi. The inter-regional trade embodied carbon between the two provinces mainly flows out to neighboring developed provinces, such as Jiangsu, Zhejiang, and Shanghai. The inflow of embodied carbon between Hunan and Hubei is mainly from Hebei, Inner Mongolia, and Shaanxi. The inter-regional trade embodied carbon in the two provinces mainly flows out to developed regions, such as Guangdong, Jiangsu, and Shanghai. It can be seen that the regional agglomeration of embodied carbon in trade is obvious. The inter-regional embodied carbon in the middle reaches of the Yangtze river mainly flows out to the economically developed regions, such as Jiangsu and Shanghai, and the inflow of trade embodied carbon mainly comes from the economically backward regions, such as Shaanxi and Inner Mongolia. Under the production responsibility system, the middle reaches of the Yangtze River provide support for economic growth in Jiangsu and Shanghai, and they also bear more responsibility for emission reduction in the division of emission reduction responsibilities. Also, the middle reaches of the Yangtze River can meet the local consumption demand by transferring the consumer goods and investment goods through inter-regional trade, which means that the middle reaches of the Yangtze river benefit from the allocation of emission reduction responsibilities under the production responsibility system. Under the consumer responsibility system, for the middle reaches of the Yangtze River, part of the emission reduction responsibility is transferred from developed areas, such as Jiangsu and Shanghai.

Industry analysis of embodied carbon in trade at the middle reaches of the Yangtze River

Next, this paper will explore the industry characteristics of embodied carbon in trade at the middle reaches of the

Yangtze River. Specifically, this section further combs and analyzes the high emission carbon lock-in industries in the middle reaches of the Yangtze River and the provinces where these industries flow out and flow in. Due to space limitations, the top 6 provinces with highest embodied emissions in trade are investigated here, which would be more beneficial to reflecting the development trend of embodied carbon in inter-regional trade.

Industry analysis of outflow of embodied carbon in trade in the middle reaches of the Yangtze River

Discussing the distribution of embodied carbon outflows to other major industries in the country is an important part of implementing industry emission reductions.

In terms of the time dimension, Table 6 reveals that embodied carbon in trade that flows from Anhui is mainly concentrated in the transportation and warehousing industry, agriculture, the chemical industry, and the electrical machinery and equipment manufacturing industry. More significantly, the growth trend of the transportation and warehousing industry in 2012 increased by more than 15% compared to 2007 and 2010. The outflow increased by nearly 4.6 million tons of CO_2. On the one hand, the outflow of the Anhui transportation and warehousing industry made up a relatively significant share of 30 industries in 2012. On the other hand, the figures show that the total outflow of 30 industries in Anhui also increased significantly. Of these top 6 outflow industries, the metal smelting and rolling processing industry, the chemical industry, agriculture, and the transportation and warehousing industry are the main sectors in Jiangxi and Hunan that emit CO_2 through trade. These 4 industries accounted for more than 67% of the total outflow of the embodied carbon of the two provinces in the same period.

More significantly, the transportation and warehousing industry in Jiangxi in 2012 increased rapidly, by nearly 20% compared with 2007 and 2010, which indicates that the relative proportion of the total outflow of the transportation and warehousing industry in Jiangxi increased. The concentrated high-carbon industry that Jiangxi flowed out by trading to

Table 6 Industry analysis of outflow and proportion of embodied carbon in trade in the middle reaches of the Yangtze River by stages (unit: 10^4 t CO_2)

Province	Year								
	2007			2010			2012		
	Industry	Outflow	Percent	Industry	Outflow	Percent	Industry	Outflow	Percent
Anhui province	25	172.79	38.65	25	172.94	42.90	25	632.55	58.24
	1	68.14	15.24	1	68.29	16.94	1	74.75	6.88
	12	50.63	11.32	12	28.13	6.98	6	71.08	6.54
	14	43.33	9.69	18	24.62	6.11	18	68.64	6.32
	18	30.55	6.83	17	20.47	5.08	14	67.97	6.26
	6	18.05	4.04	13	19.81	4.91	12	52.59	4.84
Jiangxi province	1	33.15	30.72	12	42.57	27.36	25	155.83	39.88
	12	25.78	23.89	14	42.07	27.04	14	105.29	26.94
	14	15.06	13.96	1	21.13	13.58	12	44.73	11.45
	25	11.63	10.78	25	15.63	10.05	1	26.62	6.81
	10	4.94	4.58	10	6.32	4.07	3	26.62	6.81
	6	2.61	2.42	18	3.99	2.56	6	8.98	2.30
Hubei province	25	388.64	68.73	25	384.86	59.78	6	94.61	58.84
	1	62.19	11.00	1	69.68	10.82	1	26.19	16.29
	6	28.58	5.05	26	42.25	6.56	12	10.00	6.22
	22	16.10	2.85	6	33.75	5.24	14	7.78	4.84
	26	15.51	2.74	22	29.95	4.65	7	6.26	3.89
	7	12.48	2.21	7	21.27	3.30	17	4.33	2.69
Hunan province	1	139.11	31.63	1	96.80	29.48	1	132.24	30.72
	14	134.80	30.65	14	78.23	23.82	14	72.39	16.82
	25	33.72	7.67	12	24.44	7.44	6	66.20	15.38
	26	28.60	6.50	25	38.93	11.86	12	52.88	12.28
	12	26.29	5.98	6	18.56	5.65	16	35.76	8.31
	6	24.20	5.50	26	18.42	5.61	25	31.22	7.25

other areas in 2007 is similar to that in 2010. Among the 30 industries, the proportion of transportation and warehousing is higher than 59%. In 2012, there were some changes in the proportion of some industries in Hubei compared to 2007 and 2010, namely, the food manufacturing and tobacco processing industry increased by more than 53%. The proportion of agriculture in the 30 industries increased to certain degree; meanwhile, the outflow of embodied carbon shows a trend of significant reduction, which shows that the total outflow of Hubei in 2012 was significantly lower than that in both 2007 and 2010. To conclude, the middle reaches of the Yangtze River belong to economically underdeveloped areas, and the structures between different industries are not stable enough.

Further, from the perspective of industry and region, it can be found that there is a phenomenon of high-carbon industry lock-up in the middle reaches of the Yangtze River. The results in Table 7 show that the outflow industry is mainly concentrated in the transportation and warehousing industry, agriculture, and the chemical industry. At the same time, the outflow provinces of the transportation and warehousing industry in the middle reaches of the Yangtze River in 2007 and 2010 were mainly concentrated in Jiangsu, Beijing, Tianjin, and Fujian provinces. In 2012, the outflow provinces of the transportation and warehousing industry in the middle reaches of the Yangtze River were mainly distributed in Jiangsu, Zhejiang, Shanghai, and Henan. Agriculture in Anhui and Jiangxi flowed out mainly to Shandong, Zhejiang, and Jiangsu, and agriculture in Hubei and Hunan flowed out mainly to Guangdong, Shandong, and Zhejiang. The outflow provinces of the chemical industry in the middle reaches of the Yangtze River are mainly concentrated in Jiangsu, Zhejiang, and Guangdong provinces. In general, the high emission carbon lock-in industries in the middle reaches of the Yangtze river flow out mainly to more developed regions, such as Jiangsu and Guangdong. Under the production responsibility system, the high emission carbon-locked out industries in the middle reaches of the Yangtze river are indirectly partly responsible for Jiangsu, Guangdong, and other regions.

Table 7 Provinces outflow of high emission carbon lock industry in the middle reaches of the Yangtze River

Province	Year								
	2007			2010			2012		
	25	1	12	25	1	12	25	1	12
Anhui province	Tianjin	Shandong	Zhejiang	Tianjin	Shandong	Zhejiang	Jiangsu	Shandong	Jiangsu
	Hebei	Jiangsu	Jiangsu	Jiangsu	Jiangsu	Guangdong	Jiangxi	Jiangsu	Zhejiang
	Jiangsu	Hebei	Guangdong	Beijing	Zhejiang	Jiangsu	Shanghai	Zhejiang	Guangdong
	Fujian	Zhejiang	Henan	Fujian	Beijing	Henan	Shandong	Jiangxi	Henan
	Beijing	Beijing	Hebei	Hebei	Hebei	Shandong	Zhejiang	Henan	Jiangxi
	Zhejiang	Henan	Shandong	Inner Mongolia	Henan	Shanghai	Henan	Inner Mongolia	Beijing
Jiangxi province	Tianjin	Guangdong	Zhejiang	Tianjin	Guangdong	Zhejiang	Anhui	Zhejiang	Guangdong
	Hebei	Fujian	Guangdong	Beijing	Shandong	Guangdong	Shanghai	Shandong	Jiangsu
	Jiangsu	Shandong	Jiangsu	Jiangsu	Fujian	Jiangsu	Jiangsu	Anhui	Zhejiang
	Beijing	Zhejiang	Fujian	Inner Mongolia	Zhejiang	Anhui	Shandong	Guangdong	Anhui
	Fujian	Jiangsu	Anhui	Hebei	Anhui	Fujian	Zhejiang	Jiangsu	Hunan
	Inner Mongolia	Hebei	Henan	Fujian	Jiangsu	Shanghai	Henan	Inner Mongolia	Henan
Hubei province	Tianjin	Guangdong	Guangdong	Tianjin	Guangdong	Guangdong	Guangdong	Shandong	Guangdong
	Jiangsu	Guangxi	Hebei	Beijing	Guangxi	Shandong	Hunan	Zhejiang	Jiangsu
	Hebei	Shandong	Henan	Jiangsu	Shandong	Henan	Zhejiang	Anhui	Henan
	Fujian	Jiangsu	Shandong	Fujian	Sichuan	Hebei	Jiangsu	Henan	Anhui
	Beijing	Sichuan	Jiangsu	Hebei	Xinjiang	Anhui	Henan	Inner Mongolia	Zhejiang
	Zhejiang	Yunnan	Zhejiang	Inner Mongolia	Jiangsu	Jiangsu	Anhui	Jiangsu	Hunan
Hunan province	Tianjin	Guangdong	Guangdong	Tianjin	Guangdong	Guangdong	Anhui	Shandong	Guangdong
	Jiangsu	Zhejiang	Fujian	Beijing	Zhejiang	Fujian	Jiangsu	Guangdong	Jiangsu
	Hebei	Shandong	Henan	Jiangsu	Shandong	Shanghai	Shandong	Zhejiang	Henan
	Beijing	Guangxi	Zhejiang	Hebei	Guangxi	Henan	Shanghai	Anhui	Anhui
	Fujian	Hubei	Shanghai	Fujian	Anhui	Zhejiang	Henan	Henan	Zhejiang
	Zhejiang	Fujian	Jiangsu	Inner Mongolia	Hubei	Anhui	Liaoning	Inner Mongolia	Chongqing

The order of the outflow provinces in the middle reaches of the Yangtze River in the table is from highest to lowest (from the column)

Table 8 Industry analysis on inflow and proportion of embodied carbon in trade in the middle reaches of the Yangtze River by stages (unit: 10^4 t CO_2)

Province	Year								
	2007			2010			2012		
	Industry	Inflow	Percent	Industry	Inflow	Percent	Industry	Inflow	Percent
Anhui province	1	37.36	9.58	24	61.41	10.71	25	240.98	14.34
	6	36.24	9.29	6	57.31	9.99	14	214.67	12.78
	24	35.93	9.05	18	49.11	8.56	24	185.81	11.06
	14	35.28	9.21	30	44.59	7.77	30	126.27	7.52
	25	33.87	8.68	14	41.55	7.24	13	84.82	5.05
	30	31.70	8.13	17	39.86	6.95	6	74.90	4.46
Jiangxi province	14	48.86	16.01	14	37.00	15.47	22	125.95	17.85
	26	43.87	14.37	6	24.66	10.31	14	103.91	14.72
	24	28.34	9.28	12	20.77	8.68	24	65.57	9.29
	25	22.84	7.48	22	20.25	8.47	25	58.40	8.28
	22	21.06	6.90	26	19.89	8.32	26	51.54	7.30
	12	19.08	6.25	24	12.40	5.18	11	51.12	7.24
Hubei province	6	34.73	16.73	6	32.23	14.66	22	54.39	40.63
	1	20.44	9.84	14	20.13	9.16	14	11.33	8.46
	30	15.90	7.66	24	17.91	8.15	11	11.22	8.38
	24	14.33	6.90	22	15.75	7.17	12	9.83	7.34
	12	12.78	6.15	13	14.75	6.71	24	8.69	6.49
	14	12.23	5.89	25	14.67	6.67	13	8.50	6.35
Hunan province	24	20.86	12.00	24	24.71	12.08	24	68.89	16.13
	11	17.52	10.07	6	19.62	9.59	14	49.84	11.67
	30	16.60	9.54	11	18.61	9.10	25	40.19	9.41
	1	16.53	9.50	14	15.23	7.44	22	36.04	8.44
	14	15.79	9.08	1	14.10	6.89	30	28.31	6.63
	6	15.01	8.63	30	14.07	6.88	2	24.58	5.76

Industry distribution of embodied carbon in trade at the middle reaches of the Yangtze River

Table 8 shows the main industry distributions of inflowing embodied carbon in trade at the middle reaches of the Yangtze River in 2007, 2010, and 2012.The embodied carbon in trade that inflowed from other regions to Anhui was mainly from the metal smelting and calendaring processing industry, the food manufacturing industry and tobacco processing industry, and the construction industry. The inflow of the top 6 industries increased significantly, but the proportion did not differ significantly, which implied that the inflow in Anhui increased significantly in 2012 compared with 2007 and 2010. The embodied carbon in trade inflowing from other regions to Jiangxi mainly originates from the metal smelting and rolling processing industry, the production and supply of electric power and hot power industry, the construction industry, and the wholesale and retail industry. In 2007 and 2010, the top 6 industries with the embodied carbon in import trade from other regions to Hunan are the construction industry, the metal smelting and calendaring industry, agriculture, and the petroleum processing, coking, and nuclear fuel processing industry. In 2012, the embodied carbon that inflowed from the major industries increased, while the structure between industries changed significantly. In 2010 and 2012, Hubei's main stable industries from other regions were concentrated in the food manufacturing and tobacco processing industry, the metal smelting and rolling processing industry, and the construction industry. However, the inflow of embodied carbon changed obviously in structure between different industries in 2012, with the production and supply of electric power and hot power increasing by more than 33% compared with 2007 and 2010. Generally, the inflow is less than the outflow of embodied carbon in trade in the middle reaches of the Yangtze River.

It is further found that the high emission carbon-locked inflows in the middle reaches of the Yangtze River are mainly concentrated in the metal smelting and rolling processing industry, the food manufacturing and tobacco processing industry, and the construction industry. Table 9 analyzes the major

Table 9 Inflow of provinces with high emission carbon lock industry in the middle reaches of the Yangtze River

Province	Year								
	2007			2010			2012		
	14	24	6	14	24	6	14	24	6
Anhui province	Hebei	Hebei	Jilin	Hebei	Hebei	Inner Mongolia	Inner Mongolia	Shanghai	Hubei
	Henan	Henan	Heilongjiang	Shanxi	Henan	Hebei	Hebei	Jiangsu	Heilongjiang
	Shanxi	Shaanxi	Inner Mongolia	Inner Mongolia	Inner Mongolia	Chongqing	Yunnan	Inner Mongolia	Shandong
	Shaanxi	Inner Mongolia	Shaanxi	Shaanxi	Shandong	Heilongjiang	Shanghai	Shaanxi	Jilin
	Inner Mongolia	Shanxi	Xinjiang	Henan	Shaanxi	Jilin	Henan	Shandong	Henan
	Yunnan	Jiangsu	Hebei	Xinjiang	Shanxi	Shaanxi	Shaanxi	Henan	Inner Mongolia
Jiangxi province	Shanghai	Hebei	Hunan	Hebei	Hebei	Hebei	Hebei	Anhui	Anhui
	Hebei	Shanghai	Inner Mongolia	Shanghai	Shanghai	Inner Mongolia	Inner Mongolia	Shanghai	Hubei
	Inner Mongolia	Inner Mongolia	Hebei	Inner Mongolia	Inner Mongolia	Hunan	Anhui	Henan	Jilin
	Beijing	Beijing	Jilin	Shaanxi	Shaanxi	Shaanxi	Yunnan	Shaanxi	Heilongjiang
	Shaanxi	Hunan	Guizhou	Hubei	Henan	Chongqing	Henan	Yunnan	Yunnan
	Guizhou	Henan	Shanghai	Guizhou	Hubei	Anhui	Shanghai	Jiangsu	Henan
Hubei province	Shanxi	Hebei	Yunnan	Shanxi	Hebei	Chongqing	Hebei	Henan	Hunan
	Hebei	Inner Mongolia	Hunan	Hebei	Inner Mongolia	Yunnan	Inner Mongolia	Hunan	Jilin
	Inner Mongolia	Henan	Chongqing	Inner Mongolia	Shanxi	Inner Mongolia	Yunnan	Jiangxi	Yunnan
	Henan	Hunan	Inner Mongolia	Henan	Henan	Hunan	Guizhou	Guizhou	Henan
	Shaanxi	Shanxi	Jilin	Shaanxi	Hunan	Hebei	Shaanxi	Yunnan	Heilongjiang
	Shanghai	Shanghai	Heilongjiang	Xinjiang	Shaanxi	Jilin	Gansu	Shanxi	Anhui
Hunan province	Guizhou	Hebei	Yunnan	Guizhou	Hebei	Chongqing	Hebei	Yunnan	Hubei
	Yunnan	Henan	Chongqing	Hebei	Henan	Yunnan	Inner Mongolia	Jiangxi	Yunnan
	Hebei	Yunnan	Guizhou	Yunnan	Hubei	Hubei	Yunnan	Henan	Heilongjiang
	Henan	Hubei	Henan	Shanxi	Yunnan	Guizhou	Shaanxi	Guizhou	Jilin
	Gansu	Guizhou	Hubei	Guangxi	Inner Mongolia	Hebei	Guizhou	Guangxi	Guizhou
	Guangxi	Inner Mongolia	Anhui	Jiangxi	Guangxi	Henan	Gansu	Hainan	Guangxi

The order of the inflowing provinces in the middle reaches of the Yangtze River in the table is from highest to lowest (from the column)

Table 10 Industry analysis on net outflow, net inflow, and proportion of embodied carbon in trade in the middle reaches of the Yangtze River by stages (unit: 10^4 t CO_2)

Province	Year											
	2007				2010				2012			
	Net outflow		Net inflow		Net outflow		Net inflow		Net outflow		Net inflow	
	Industry	EO (%)	Industry	EI (%)	Industry	EO (%)	Industry	EI (%)	Industry	EO (%)	Industry	EI (%)
Anhui province	25	138.91 (243.43)	24	− 35.93 (− 62.96)	25	135.20 (− 79.27)	24	− 61.41 (36.01)	25	391.57 (− 65.91)	16	− 65.51 (11.03)
	1	30.78 (53.95)	30	− 30.79 (− 53.96)	1	35.26 (− 20.67)	6	− 43.45 (25.47)	1	24.93 (− 4.20)	24	− 185.78 (31.27)
	12	24.21 (42.42)	6	− 18.19 − 31.87)	13	1.43 (− 0.84)	14	− 33.50 (19.64)	18	13.44 (− 2.26)	14	− 146.69 (24.69)
	14	8.05 (14.11)	16	− 9.30 (− 16.29)	–	–	30	− 33.32 (19.54)	–	–	22	− 131.25 (22.09)
	18	6.86 (12.02)	15	− 8.38 (− 14.69)	–	–	18	− 24.50 (14.36)	–	–	30	− 101.15 (17.03)
	2	3.82 (6.69)	27	− 8.06 (− 14.12)	–	–	16	− 21.89 (12.83)	–	–	13	− 69.58 (11.71)
Jiangxi province	1	17.72 (− 8.98)	26	− 42.43 (21.50)	12	21.80 (− 64.66)	6	− 21.02 (62.35)	25	155.83 (− 96.61)	22	− 125.46 (77.78)
	12	6.70 (− 3.39)	14	− 33.80 (17.13)	1	16.08 (− 47.70)	22	− 20.23 (60.02)	3	26.62 (− 16.50)	24	− 65.57 (40.65)
	–	–	24	− 28.34 (14.36)	25	15.63 (− 46.37)	24	− 12.39 (36.76)	12	16.97 (− 10.52)	11	− 51.03 (31.64)
	–	–	22	− 21.05 (10.67)	14	5.07 (− 15.03)	11	− 10.90 (32.34)	1	16.88 (− 10.47)	13	− 26.33 (16.32)
	–	–	30	− 16.91 (8.57)	30	3.68 (− 10.91)	13	− 5.47 (16.23)	26	3.20 (− 1.98)	2	− 24.54 (15.21)
	–	–	6	− 12.59 (6.38)	26	1.43 (− 4.23)	9	− 5.06 (15.00)	30	1.76 (− 1.09)	4	− 17.74 (11.00)
Hubei province	25	378.76 (105.85)	24	− 14.33 (− 4.00)	25	370.19 (87.31)	24	− 17.91 (− 4.22)	6	88.42 (328.02)	22	− 54.38 (− 201.73)
	1	41.75 (11.67)	11	− 11.98 (− 3.35)	1	55.32 (13.05)	12	− 11.96 (− 2.82)	1	24.38 (90.43)	11	− 11.21 (− 41.58)
	26	12.74 (3.56)	12	− 10.83 (− 3.03)	26	39.81 (9.39)	14	− 10.63 (− 2.51)	7	5.64 (20.92)	24	− 8.69 (− 32.22)
	22	8.15 (2.28)	30	− 7.54 (− 2.11)	7	15.67 (3.70)	16	− 6.39 (− 1.51)	5	3.75 (13.93)	13	− 6.80 (− 25.21)
	7	5.45 (1.52)	16	− 7.05 (− 1.97)	22	14.20 (3.35)	11	− 5.97 (− 1.41)	15	1.47 (5.47)	14	− 3.55 (− 13.17)
	15	0.54 (0.15)	6	− 6.15 (− 1.72)	27	2.83 (0.67)	13	− 5.49 (− 1.29)	17	1.28 (4.74)	25	− 3.02 (− 11.19)
Hunan province	1	122.58 (46.11)	24	− 18.94 (− 7.12)	1	82.70 (66.83)	24	− 22.81 (− 18.43)	1	114.96 (3378.54)	24	− 68.82 (− 2022.63)
	14	119.02 (44.77)	11	− 11.47 (− 4.31)	14	63.00 (50.91)	11	− 17.35 (− 14.02)	6	47.85 (1406.19)	22	− 36.04 (− 1059.16)
	25	27.57 (10.37)	30	− 5.11 (− 1.92)	25	28.63 (23.13)	22	− 8.81 (− 7.12)	12	34.81 (1023.15)	2	− 24.56 (− 721.89)
	26	25.69 (9.66)	27	− 3.49 (− 1.31)	12	13.80 (11.15)	2	− 4.76 (− 3.84)	14	22.55 (662.76)	30	− 12.42 (− 365.00)
	12	15.58 (5.86)	4	− 2.49 (− 0.94)	26	13.46 (10.88)	27	− 4.76 (− 3.84)	16	11.42 (335.65)	11	− 11.33 (− 333.11)
	6	9.18 (3.45)	22	− 2.38 (− 0.89)	16	4.62 (3.74)	13	− 3.95 (− 3.19)	19	0.62 (18.13)	28	− 11.12 (− 326.84)

EO/EI (%): net outflow/net inflow (the proportion of the 30 industries)

Table 11 Influencing factor decomposition on inflow of embodied carbon in trade at the middle reaches of the Yangtze River by stages (Unit: $MtCO_2$)

Period	Driving factor	Anhui province		Jiangxi province		Hubei province		Hunan province	
		f	Contribution rate (%)	*f*	Contribution rate (%)	*f*	Contribution rate (%)	*f*	Contribution rate (%)
2007~2010	Energy carbon emission effect	1.86	9.02	− 0.20	25.99	10.10	32.28	− 1.28	7.02
	Energy intensity effect	− 7.47	− 36.22	− 5.58	736.60	− 104.71	− 334.77	− 50.27	276.18
	Inter-industry correlation effect	− 0.17	− 0.80	− 0.01	0.99	− 3.43	− 10.96	− 0.10	0.56
	Scale effect	60.44	293.00	22.57	− 2979.14	121.03	386.91	63.45	− 348.60
	Structure effect	− 34.03	− 165.00	− 17.54	2315.56	8.30	26.54	− 30.00	164.84
2010~2012	Energy carbon emission effect	− 13.80	− 8.30	− 0.88	− 1.43	1.09	− 0.55	− 6.02	− 12.98
	Energy intensity effect	33.82	20.36	− 2.90	− 4.75	8.13	− 4.13	8.08	17.44
	Inter-industry correlation effect	1.03	0.61	0.26	0.42	− 0.33	0.17	17.20	37.10
	Scale effect	120.35	72.44	7.64	12.51	− 44.39	22.55	46.51	100.32
	Structure effect	24.73	14.89	56.97	93.25	161.35	81.96	− 19.42	− 41.88
2007~2012	Energy carbon emission effect	− 7.88	− 4.22	− 1.26	− 2.09	6.55	− 3.96	− 8.02	− 30.07
	Energy intensity effect	29.09	15.58	15.17	− 25.14	− 35.87	21.67	− 41.86	− 157.04
	Inter-industry correlation effect	0.68	0.36	0.21	0.35	− 3.20	1.93	18.33	68.77
	Scale effect	208.35	111.57	48.42	80.24	12.79	− 7.73	121.10	454.26
	Structure effect	− 43.49	− 23.29	28.14	46.64	− 145.85	88.09	− 62.89	− 235.92

inflowing provinces in the high carbon-locked industries in the middle reaches of the Yangtze River. It can be seen from Table 9 that the inflowing provinces of metal smelting and rolling processing industries in the middle reaches of the Yangtze River are mainly from Hebei, Inner Mongolia, and Shaanxi provinces. In 2007, the inflowing provinces of the middle reaches of the Yangtze River were concentrated mainly in Hebei, Henan, and Inner Mongolia. In 2012, the inflow provinces of the middle reaches of the Yangtze River were mainly from Henan, Yunnan, and Shaanxi. The inflow provinces of food manufacturing and tobacco processing industries in the middle reaches of the Yangtze River are mainly from the provinces of Jilin, Inner Mongolia, and Heilongjiang. In general, the industries with high emission carbon inflows in the middle reaches of the Yangtze River are mainly from areas lacking in economic development, such as Hebei, Henan, and Inner Mongolia. Under the production responsibility system, Hebei, Henan, and Inner Mongolia indirectly bear part of the responsibility for the inflow of high emission carbon-locked industries in the middle reaches of the Yangtze River.

Industry analysis on net outflow and net inflow of embodied carbon

Table 10 shows the industrial distribution in terms of net outflow (inflow) of embodied carbon in trade in the middle reaches of the Yangtze River. The net outflow industries that flow from Anhui to other regions are mainly the transportation and warehousing industry and agriculture. The most significant is the transportation and warehousing industry, whose net outflow accounts for 243.43%, − 79.27%, and − 65.91%, of the total net outflow of all industries in Anhui, respectively. This shows that all industries in Anhui were mainly net outflow in 2007 and mainly net inflow in 2010 and 2012. The main net inflow industries were the construction industry and the general and special equipment manufacturing industry. The main net outflow industry in Jiangxi was the agriculture and chemical industry in 2007 and 2010, whereas, in 2012, the main net outflow industries were the transportation and warehousing industry and the oil and gas extraction industry. It is not difficult to find that the main net outflow industry in Jiangxi was negative at that time, indicating that the industries in Jiangxi were mainly net inflow. Hubei was mainly net inflow, with the main net outflow industries in Hubei being in the transportation and warehousing industry and agriculture in 2007 and 2010, and the main net inflow industries being the construction industry and the chemical industry. In 2012, the main net outflow industries in Hubei were the food manufacturing and tobacco processing industry and agriculture. The main net inflow industries were the production and supply of electric power and hot power industry and the petroleum processing, coking, and nuclear fuel processing industry. Hunan is mainly net outflow, with the main net outflow industries being agriculture, the metal smelting and calendaring industry, and the chemical industry. The main net inflow industries are the construction industry and the petroleum processing, coking, and nuclear fuel processing industry.

As described above, the net inflow of embodied carbon in trade 30 industries in the middle reaches of the Yangtze River is generally smaller than the net outflow. The developed areas have grafted high-energy, high-pollution, and energy-intensive industries to less developed areas or underdeveloped areas through inter-regional trade, and these are processed and manufactured by the less developed areas or underdeveloped areas. Although carbon emissions from underdeveloped areas have been reduced, the carbon emissions in less developed areas or underdeveloped areas have increased. It seems reasonable to transfer embodied carbon in trade by industries and that the "consumer should be held responsible"; however, if consumers only hold the responsibility, producers may lose the initiative to reduce carbon emissions. Therefore, it has become particularly important to define the responsibility of "production and consumption."

SDA decomposition of outflow of embodied carbon in trade at the middle reaches of the Yangtze River

Based on the above results, we further explore how the changes of various factors affect the growth of the embodied carbon that flow out by trade, which will be beneficial when defining the responsibility of "production and consumption" reasonably. Therefore, the SDA method is further applied to study the contribution of relevant factors. To this end, the following study is based on the formula of Table 1, to explore how the energy intensity effect, the energy carbon emission effect, the inter-industry correlation effect, the scale effect, and the structural effect impact the increase of embodied carbon in the flow out by trade.

As shown in Table 11, the total amount of product outflow has the greatest impact on promoting the embodied carbon in the outflow trade between regions in different time periods. In particular, the contribution of the scale effect in Anhui in different time periods is 60.44, 120.35, and 208.35 Mt CO_2, respectively, and the corresponding contribution rates are 293.01%, 72.44%, and 111.57%, respectively. It can be seen that the embodied carbon emissions of outflow trade in the middle reaches of the Yangtze River increase. The main reason is the expansion of the total outflow, that is, the impact of the scale effect is the greatest. This means that, as the outflow volume continues to increase in the future, it will be more difficult to reduce the total amount of carbon emissions embodied in the outflow from the middle reaches of the Yangtze River. Throughout the study period, the inter-industry correlation effects of each year were aggregated and positive, that is, the change in the intermediate input technology increased the implicit carbon emissions of the outflow trade, but its impact value was smaller than was the scale effect. The energy carbon emission effect and the structural effect are very similar to the decomposition results of the implicit carbon change in outflow trade. The main performance is the hindrance, that is, the increase in the proportion of unit energy carbon emissions and trade outflow products inhibits the increase of implicit carbon emissions from outflow trade. It was further found that, during the entire study period, the overall energy intensity effect was also negative, that is, the improvement of energy efficiency inhibited the increase of imported embodied carbon emissions.

Conclusions and implications

This paper takes the middle reaches of the Yangtze River as the research area and applies an input–output model of 2007, 2010, and 2012 to calculate the embodied carbon in trade at the middle reaches of the Yangtze River. At the same time, the SDA method is used to further explore the driving factors that affect the embodied carbon in trade. The results are as follows:

1) Production-based CO_2 emissions from Hubei and Hunan were higher than consumption-based CO_2 emissions in 2007, 2010, and 2012. Generally speaking, the production-based CO_2 emissions from the middle reaches of the Yangtze River were higher than the consumption-based emissions. Due to the fact that the accounting method for the production-based emissions conceals the transfer of CO_2 emissions from products and services for output, under the production responsibility system, the middle reaches of the Yangtze River indirectly undertake some responsibility for reducing the emissions of the other areas.
2) Based on the analysis of multi-regional embodied carbon in trade, Hunan and Hubei are mainly net outflow regions and Anhui and Jiangxi are mainly net inflow regions. At the same time, the inter-regional embodied carbon in trade at the middle reaches of the Yangtze River flows out mainly to relatively developed areas, such as Jiangsu and Shanghai. The inflow of embodied carbon comes mainly from the relatively backward economic development areas, such as Shaanxi and Inner Mongolia. It can be seen that the regional agglomeration characteristics are obvious.
3) From the perspective of the entire industry, Anhui and Jiangxi are mainly net inflow regions, with the main net outflow industries in Anhui being the transportation and warehousing industry and agriculture, and the main net inflow industries are the construction industry and the general and special equipment manufacturing industry. The main net outflow industries in Jiangxi were agriculture and the chemical industry in 2007 and 2010, whereas the transportation and warehousing industry and the oil

and gas extraction industry were more dominant in 2012. Hubei is mainly net outflow, with the main net outflow industries in 2007 and 2010 being the transportation and warehousing industry and agriculture and the main net inflow industries being the construction industry and the chemical industry. The main net outflow industries of Hubei in 2012 were the food manufacturing and tobacco processing industry and agriculture. The main net inflow industries were the production and supply of electric power and hot power industry and the petroleum processing, coking, and nuclear fuel processing industry. Hunan is mainly net outflow, with the main net outflow industries being agriculture, the metal smelting and calendaring industry, and the chemical industry, while the main net inflow industries are the construction industry and the petroleum processing, coking, and nuclear fuel processing industry.

4) From the perspective of region and industry, the embodied carbon in the middle reaches of the Yangtze River has a high carbon lock. Specifically, the main high emission carbon-locked outflow industries are the transportation and warehousing industry, agriculture, and the chemical industry. The high emission carbon-locked outflow industry flows out mainly to Jiangsu, Guangdong, and other economically developed regions. The main high emission carbon-locked inflow industries in the middle reaches of the Yangtze River are the metal smelting and rolling processing industry, the food manufacturing and tobacco processing industry, and construction, and the industries with high emission carbon lock-in are derived mainly from economic development levels in Hebei, Henan, and Inner Mongolia.
5) After exploring the factors that impact on the increase of embodied carbon in trade, the main reason for the increase in the embodied carbon emissions of outflow trade in the middle reaches of the Yangtze River is the expansion of the total outflow, that is, the scale effect has the greatest impact. The inter-industry correlation effects of each year are summarized as positive, that is, the change of the intermediate input technology makes the implicit carbon emissions of the outflow trade increase, but the impact value is smaller than the scale effect. Energy carbon emission effects, energy intensity effects, and structural effects are very similar to the decomposition of embodied carbon changes in outflows, mainly as a hindrance.

According to the above findings, policy implications can be summarized as follows. First, under the production responsibility system, less-developed and underdeveloped areas indirectly undertook some emissions' responsibilities for other provinces. Therefore, regarding the responsibility of reducing emissions, carbon compensation measures should be adopted in developed areas to compensate less-developed and underdeveloped areas, because they have suffered huge losses. At the same time, less-developed and underdeveloped areas should set corresponding emission reduction plans for high-carbon industries and strive to achieve a win-win situation in the green and low-carbon industries. In developed areas, high-energy, high-pollution, and energy-intensive industries have transferred to less-developed and underdeveloped areas through inter-regional trade. Although carbon emissions from underdeveloped areas have been reduced, carbon emissions in less developed areas and underdeveloped areas have been increased. The total carbon emissions of the whole country are still increasing. Some scholars state that carbon emission reduction responsibility can be defined as "the consumer should be held responsible"; however, if only the consumer needs to be responsible, then producers may lose their motivation to reduce carbon emissions.

Second, on the basis of distinguishing responsibilities between production and consumers, this paper redefines the responsibility of emission reduction combined with factors affecting the growth of embodied carbon in trade. Apart from industrial structure showing greater changes in certain years, based on the scale effect, developed regions transfer a large number of products that are short of resources in their region through trade, while carbon emissions remain in underdeveloped regions. Therefore, it is more appropriate for consumers to pay the bill to avoid the situation that consumers only enjoy the fruits and do not undertake obligations. As for the energy intensity effect and the energy carbon emission effect, "producers and consumers should be jointly responsible" is more reasonable. The increase in CO_2 emissions comes mainly from low energy use efficiency of producers and high carbon output structure, and producers have a responsibility to actively reduce their carbon emissions. Consumer demand for energy-intensive products in developed regions has increased CO_2 emissions, so the combination of production and consumer emissions' reductions will help improve overall emissions' reductions.

Lastly, structural effects reflect the types of trade products in different regions; the products that are transferred out are basically abundant local products, whereas the products that are transferred in are mainly scarce products in the region. Therefore, from a perspective of sharing responsibility for emission reduction, for some provinces, a number of trade products transferring to other regions would be more profitable than those transferred out, and thus, the consumers should be held responsible for reducing emissions in regional climate. Also, the lower industrial technology in developed regions is based on the development before emissions, whereas, on the other hand, the producers also have the obligation to improve their own industry structure and guide the upgrading of the industry.

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