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Research article

Embodied carbon emissions transfers via inter-regional trade: evidence from value-added extended decomposition model in China

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HIGHLIGHTS

- This paper calculates embodied carbon emissions via inter-regional trade in China.
- An exogenous treatment of China's regional input-output table is carries out to make the intermediate input-output relationship between any two regions can be expressed by the square matrix of intermediate consumption coefficient.
- A value-added extended decomposition model is applied to avoid carbon leakage and double calculation in traditional methods.
- Carbon emission network analysis have been conducted not only to uncover embodied carbon emissions transfer characteristics at regional level, but also to identify the major carbon emitters and their complex relations.

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ABSTRACT

The allocation of carbon emission reduction responsibility is severe issue in China for these years. In case to find a fairer and more effective way to divided the responsibility to each region of China, this paper examines embodied carbon emissions (ECEs) transfers in China's inter-regional trade by applying value-added extended decomposition model. This study allows policymakers to trace CO_2 emissions at regional levels and provides three key findings. Firstly, using novel data on the physical consumption of energy by region, we observe a strong and robust negative association between the regional direct CO_2 emission coefficient and the regional economic development level. Secondly, employing the latest inter-regional input-output table of China to calculate ECEs and uncover transfer characteristics via inter-regional trade, results show that central region, eastern region and northern region are the three highest ECEs regions. Thirdly, ECEs in value-added trade are generally transferred from inland China to coastal areas of China. Northeast region, north coastal region, central region and northwest region are net ECEs outflow regions, the rest regions are net ECEs inflow regions.

1. Introduction

The Sixth Assessment Report of Intergovernmental Panel on Climate Change (IPCC) notes that the global average temperature will exceed 1.5 °C above pre-industrial levels by 2030 (2021), and the breaking of this threshold means more catastrophic challenges for the planet. Global warming will increase sea level, trigger extreme climate, and cause serious issues in energy, food, water, threatening the survival and development of humanity. So actively reducing carbon emission to cope with global warming has become a common goal in countries around the world (Zhong et al., 2021; Chang et al., 2019; Martin and Saikawa, 2017). In 2015, nearly 200 countries attended the United Nations Climate Change Conference and adopted the ‘Paris Agreement’, promising to control the global temperature rising within 2 °C compared with pre-industrial period. Especially China, who has surpassed the United States being the world's largest emitter of CO_2 emissions (Zhou et al. (2021)), is making tangible efforts to cope with global warming. At the Copenhagen conference in 2009, China made a carbon emission reduction promise of 40%–45% by 2020 compared with the 2005 level (http://www.gov.cn/xinwen/). At the 75th United Nations General Assembly in 2020, China announced that it would take more effective measures, striving to reach the peak of carbon dioxide emissions by 2030 and to

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achieve carbon neutrality by 2060. To fulfill its pledges, China has introduced a series of policy tools (Lin and Liu, 2010; Duan and Hu, 2014), i.e., the National Climate Change Program.

Carbon emission reduction policies would be inefficient if policymakers ignore the huge gap among regions on energy structure (Liu et al., 2015) and huge amount among regions on trade. Considering that China is a large country with unbalanced efficiency of energy among its major regions, the level of carbon emissions are significantly different (Tan et al., 2008; Feng et al., 2009; Pan et al., 2013; Liu and Fan, 2014; Liu et al., 2015). Besides, with the obvious trend of domestic market integration, trade among regions in China has become more active, and carbon transfers embodied in regional trade are increasing. Thus, policymakers should fully consider the amount and direction of carbon emission transfer embodied in inter-regional trade when formulating regional carbon peak time and path. Furthermore, the industrial carbon emission intensity of each region will provide ideas to explore the causes of carbon emission transfer. In sum, the main purpose of this paper is to uncover energy related ECEs transfer characteristics via inter-regional trade in China, providing regional carbon emission reduction advice to policymakers.

The core problem of promote regional carbon reduction is to calculate carbon emission amount fairly. In fact, carbon emissions have been calculated widely by traditional models which are always unfair and inefficient. Production-based model (Davis and Caldeira, 2010; Liddle, 2018a, 2018b; Hasanov et al., 2018; Spaiser et al., 2019) is the most widely used model, meaning that carbon emissions are calculated based on goods and services produced within a country's territory. Though this model has strong operability, it has a serious flaw of causing carbon leakage[1]. On the contrary, consumption-based model (Jose et al., 2020; Yan et al., 2013; Knight and Schor, 2014; Zeeshan et al., 2020) can solve the carbon leakage problem by calculating the carbon emission embodied in imports. Thus, consumption-based model is beneficial for the developing countries but unfavorable for the developed countries, being still unfair. With the development of I–O methodology (Peters, 2008), some studies apply the multi-regional input-output method (MRIO) and the emissions embedded in bilateral trade method (EEBT) to measure carbon emissions. But these two considerable accounting methods can lead to double counting problem of implicit CO_2 emission flows caused by intermediate products crossing several borders repeatedly (Johnson, 2014; Johnson and Noguera, 2012). Thus, this paper calculates ECEs via inter-regional trade in China using value-added extended decomposition model which can overcome the shortcomings of traditional methods.

Although a plethora of researchers have calculated world carbon emissions (Xu et al., 2021), however, China ECEs and transfer characteristics via inter-regional trade remain far from clear. Yan et al. (2020) and Gao et al. (2020) have measured the ECEs of China, while they both fails to study regional carbon emission features. It's important to emphasize that regions in China are significantly and systematically different from each other in terms of their carbon emission intensity and total carbon emission; this is the case because of geographical location, energy structure, and economic development level. Besides, existing researches study regional (Zhou et al., 2018; Zhang, 2017) or provincial (Wang et al., 2018) carbon emission transfer characteristics all based on traditional methods which are unfair. Given that, this paper use the value-added extended decomposition model to study the transfer characteristics of ECEs in China, providing a fair way to allocate the carbon emission responsibility of each region in China.

This paper extends the literature in several aspects. Firstly, this is a pioneering effort to analyze ECEs from the aspect of value-added trade. This paper formally generalizes two independent lines of research into a unified conceptual framework: ECEs mitigation duty and value-added trade. Following this technique, this paper calculates ECEs and transfers from inter-regional trade, successfully avoiding carbon leakage and double calculation in traditional methods. Therefore, this paper provides new insights into the exploration of intended regional abatement responsibility regarding value-added by sources. Secondly, this paper creatively carries out exogenous treatment of China's regional input-output table, making it suitable for the extended value-added decomposition model. The intermediate input-output relationship between any two regions in the WIOD table can be expressed by the square matrix of intermediate consumption coefficient. But in China's regional input-output table, only the input-output relationship between regions within the system can be expressed by the square matrix of intermediate consumption coefficient, the economic relationship between regions within the system and regions outside the system can only be described by ‘import’ and ‘export’. So this paper carries out exogenous treatment of China's regional input-output table, fills the deficiency in this field and provides a theoretical basis for future research. Thirdly, this paper allows policymakers to trace the inter-regional CO_2 emission footprints alongside the regional trade network. A net carbon transfer table is first put to visualize ECEs net flows of value-added trade, which helps to address the CO_2 emission reduction responsibility regarding inter-regional trade.

The organization of the paper is given as: Section two would review the theoretical and empirical literature, Section three consists of methods, description of data, and variables. Section four contains results and discussion. The last section describes conclusions and policy implications.

2. Literature review

This paper is mainly related with three different lines of studies.

First, this paper is related to the topic of ECEs in trade. Numerous studies have shown that the share of ECEs in trade on global carbon emissions is increasing continuously (Shui and Harriss, 2006; Liu et al., 2010; Li and Hewitt, 2008; Sato, 2014; Xu et al., 2017). Compared with ECEs in regional trade within a country, scholars prefer to study ECEs in global trade, especially between the developed and developing countries. Xu et al. (2021) aims to measure the worldwide embedded emissions in value-added trade. Besides, Du et al. (2011) and Li and Hewitt (2008) have studied the carbon emissions implied by Sino-US trade, and Liu et al. (2010) have analyzed CO_2 emissions embodied in Japan-China trade.

Owing to a lack of statistical data on domestic trade, for a long time, most studies focused on CO2 emissions implied in trade between countries, only few studies do research from perspective of inter-regional trade. That doesn't mean inter-regional trade is unimportant, on the contrary, inter-regional trade is the barometer of a country's economy due to vertical specialization. Since 2015, studies on CO2 emissions at the regional level in China have turned up, but these studies only examined individual province, municipality or other regional unit (Mortimer and Grant, 2008) rather than regions all over the country.

Second, this paper is associated with studies focus on carbon transfers caused by trade. Sato (2014) has found that the share of China's export embodied carbon on total carbon emissions rose from 10% in 1995 to 45% in 2007, while the change for the United States, Japan and The United Kingdom were 5%–13%, 6%–22% and 12%–29%, respectively. Developed countries (such as the United States, Japan and the European Union) are usually net importers of carbon emissions (Wyckoff and Roop, 1994; Ahmad and Wyckoff, 2003; Koesler et al., 2016; Xu et al., 2021), while developing countries (such as China, Russia and India) are usually net exporters of carbon emissions (Guan and Reiner, 2009; Meng et al., 2016; Wu et al., 2020; Xu et al., 2021).

With an obvious trend of domestic market integration, trade among regions in China has become more active, thus scholars have also begun to pay attention to carbon transfer between regions or cities in China.

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[1] Carbon leakage problem refers to that developed countries transfer carbon emissions to developing countries by transferring high polluting industries to developing countries or increasing imports, so as to decrease their own carbon emissions and decrease their reduction responsibility for emissions.

Zhao et al. (2015) found that about 23% of PM2.5 emissions, 33% of sulfur dioxide emissions, and 31% of nitrogen oxide emissions in China were caused by demand outside the province rather than within the province. Wang et al. (2018) investigates the carbon footprints and embodied CO_2 transfer among 30 provinces of China in 2007 and 2010, and finds that ECEs transfer from the developing and energy-abundant provinces like Hebei and Inner Mongolia to the developed coastal provinces. Zhou et al. (2018) also argues that ECEs have mainly transferred from less developed regions like northwest to developed regions like east coast.

Third, this paper is relevant to studies concerned with the methods of measuring embodied carbon emissions. Reasonable calculation methods of carbon emission can motivate governments, enterprises and individuals to curb carbon emissions. At present, there are two main research methods of carbon emission calculation, namely, the life-cycle assessment (LCA), and the input-output method. The LCA method has provided a new idea for measuring embodied carbon. However, this methodology is suitable for microscopic quantification as it requires integrated data, significantly limiting its employment. So we mainly discuss the input-output method in this paper.

Input-output analysis is classified as single-region input-output (SRIO) and multi-region input-output (MRIO) method. SRIO analyzes greenhouse gas emissions caused by the final demand of a country or region, assuming that the carbon emission coefficients of foreign countries and domestic countries are the same. MRIO was first proposed by Miller (1963, 1966), calculating the carbon emissions from trade among countries or regions. However, the intermediate products might cross the borders repeatedly, accompanied by flows of implicit CO2 emissions, and thus precisely lead to a widely neglected problem of repeated calculation (Koopman et al., 2014), which distorts the ECES by inter-regional trade to some extent.

To solve this the problem of double accounting, Koopman et al. (2014) and Wang et al. (2013) make further progress and divide total value-added exports into four categories: domestic value-added that is eventually absorbed abroad, domestic value-added that returns to the country after export, foreign value-added and pure double-counting items. Subsequently, Li and Pan (2016) and Pan and Li (2018) integrate the domestic and foreign value chains into a unified framework to study the interaction of added value among China's regions and between China and Asia-Pacific economies. All these studies apply the value-added trade accounting method to calculate and discuss the value-added in exports, few put research on the carbon emissions hidden in trade until now.

According to researches on value-add trade (Koopman et al., 2014; Li and Pan, 2016; Wang et al., 2013; Pan and Li, 2018) and carbon emission intensity (Chen et al., 2021), this paper is the first to build ECEs measurement model by combing the value-added extended decomposition model and industrial carbon emission intensity model. The advantages of this model is as follows: First, it can solve the double calculation problem. Second, it can clearly show the amount and transfer path of ECEs from regional value-added trade in China. Third, this model makes it possible for us to find out the reasons for the transfer from the perspective of industrial structure and regional trade.

There are three marginal contributions of this paper. First, previous studies have mainly focused on the measurement of ECEs in global trade. In most cases, trade have included between developing countries and developed countries. In contrast, this paper focuses on ECEs via inter-regional trade in China. Thus, this paper make a contribution to literature on ECEs in domestic trade. Second, the generation of carbon transfer is always associated with specific sectors, however, little attention has been paid to analysis carbon transfer at an industrial level. This paper makes a unique contribution to the literature by calculating industrial carbon emission intensity as a key driving factor of ECEs transfer. Third, this paper represents an important advance as it applies the value-added extended decomposition model to analyze the ECEs transfers via inter-regional trade, successfully solving drawbacks of unfairness and double calculation of traditional models.

Table 1. China's regional division.

Region	Province
the Northeast Region (NE)	Heilongjiang, Liaoning, Jilin
the Beijing-Tianjin Region (JJ)	Beijing, Tianjin
the Northern Coastal Region (NC)	Hebei, Shandong
the East Coastal Region (EC)	Shanghai, Jiangsu, Zhejiang
the Southern Coastal Region (SC)	Fujian, Guangdong, Hainan
the Central Region (MR)	Shanxi, Henan, Anhui, Hubei, Hunan, Jiangxi
the Northwest Region (NW)	Inner Mongolia, Shanxi, Ningxia, Gansu, Qinghai, Xinjiang
the Southwest Region (SW)	Sichuan, Chongqing, Guangxi, Yunnan, Guizhou, Tibet

Table 2. Industrial division.

Number	Industrial Sector	Number	Industrial Sector
1	Agriculture	5	Power, Steam, Hot Water, Gas, and Tap Water Supply
2	Mining and Selecting Industry	6	Construction Industry
3	Light Industry	7	Commerce, Transportation
4	Heavy Industry	8	Other Services

3. Materials and method

3.1. Industrial carbon emission intensity model

Based on the classification criteria of the inter-regional input-output table of eight regions and eight sectors in 2007, this study divides China into eight regions (Table 1) and divides every region into eight sectors[2] (Table 2). This regional division can not only follow the general laws of regional economic development but also facilitate the development of research issues (Chen et al., 2021).

The main source of carbon dioxide in the atmosphere is the burning of fossil fuels, so we only considered energy-related carbon emissions embodied in trade. For reasons of the data availability and the research accuracy, this study choose the coefficient method to calculate the energy consumption intensity of each industry and region. According to Chen et al. (2021) and the'IPCC Guidelines for National Greenhouse Gas Inventories', ten fossil energy sources are selected, namely, raw coal, coke, crude oil, gasoline, kerosene, diesel, fuel oil, liquefied petroleum gas, refinery dry gas, and natural gas[3]. Data is from *China Energy Statistical Yearbook (2013)* and *China Statistical Yearbook (2013)* of province and autonomous region in China.

The calculation formula of industrial carbon emission intensity is as follows (Zhang and Hong, 2013; Zhang, 2017):

$$\theta_i^j = \frac{\sum_k^m f_k p_i^{jk}}{X_i^j} \quad (k = 1,\ 2,\ 3\ldots\ldots.,\ m) \tag{1}$$

θ_i^j represents the direct CO_2 emission intensity of sector j in region i, where the unit is 10,000 tons/10,000 yuan, it means the CO_2 emission directly caused by the production of unit value products realized by this

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[2] The principle of division of eight regions is different from that of seven regions including Northeast region, North region, Central region, East region, South region, Northwest region, and Southwest region which are divided according to the geographical position.

[3] The inter-regional input-output table includes the power and heat industries, considering that the consumption of power and heat will not directly generate CO_2 emissions, the energy consumption of power and heat is not included here.

sector. p_i^{jk} represents the physical consumption of energy k by sector j in region i, where the unit is 10^4 tons or 10^9 m^3 X_i^j represents the total output of sector j in region i measured by currency, where the unit is 10,000 yuan. f_k represents the CO_2 emission coefficient of energy k which equals the average low calorific value (CV) × the carbon content per unit calorific value (CCF) × carbon oxidation factor (COF) × 3.66667 (Luo, 2016; Wang, 2018). The equation (Eq. 2) is:

$$f_k = CV_k \times CCF_k \times COF_k \times \frac{44}{12} \tag{2}$$

Data of CV is from *China Energy Statistical Yearbook (2013)*. Data of CCF and COF is from China Provincial Greenhouse Gas Inventory Compilation Guidelines.

Energy consumption is subject to the data in the provincial energy balance table of *China Energy Statistical Yearbook (2013)*. According to the energy consumption proportion in *the provincial statistical yearbook*, this study divides the energy consumption of industries in the energy balance table into light industry and heavy industry.

Owing to the lack of energy consumption and energy balance tables for different sectors in Tibet, this study collects the data from the paper Calculation of CO_2 emissions from energy consumption and industrial production in Tibet' to obtain the energy consumption of different sectors in Tibet Zhao et al. (2016).

3.2. Value-added extended decomposition model

The data in this paper is from *the 2012 China Multi-Regional Input-Output Table of 31 Provincial Units* which is compiled by 'Key Laboratory of Regional Sustainable Development Modeling', Chinese Academy of Sciences (CAS). The data can clearly describe the economic flow input source and use direction of various departments between many regions, and it's a necessary precondition for accurately estimating embodied carbon emissions transfers via inter-regional trade. However, the latest version is the 2012 which is not timely[4].

Koopman et al. (2014) and Wang et al. (2013) all use the input-output table published by the world input-output database (WIOD). The product consumption coefficient matrix which is used to represent the input-output relationship between any two countries or regions can be found in this table. However, the inter-regional input-output table adopted in this study considers China as a system, and the consumption coefficient matrix can only be used to represent the input-output relationship among eight regions of China. As for the input-output relationship between each region in China and the outside of the system can only be described by imports and exports. Therefore, this study extends the work of Koopman et al. (2014) and Wang et al. (2013) by conducting exogenous treatment of the regions outside the system (Li and Pan, 2016; Pan and Li, 2018).

Leontief first proposed the input-output method in 1936, then Miller (1966) applied input-output technology to study the economic impact between different regions. Assuming that a country has G regions and N industries, the outflow E_{rs} from region r to region s includes both intermediate and final products from region r to region s, which can be shown as:

$$E_{rs} = A_{rs}X_r + Y_{rs} \tag{3}$$

Based on Eq. (3), we let E_{r^*} *be* the gross outflow from region r to all others regions and countries, the formula can be written as:

$$E_{r^*} = \sum_{r \neq s} E_{rs} + E_{r,row} \tag{4}$$

where $A_{rs} = x_{rs}/X_{rs}$ ($N \times N$ matrix) represents the direct consumption coefficient matrix of region r to region s. X_r ($N \times 1$vector) represents the total outflow of region r, Y_{rs} ($N \times 1$ vector) represents the final product outflow of region r to region s, and $E_{r,row}$ (N × 1 vector) represents the total exports of region s to countries and regions outside the system.

After combining Eqs. (3) and (4), we can express the total out of region r as:

$$X_r = \sum_{s=1}^{n} (A_{rs}X_r + Y_{rs}) + E_{r,row} \tag{5}$$

Then conducting the computing transformation on the basic of Eq. (5), we can get:

$$X_r = \sum_{s=1}^{n} B_{rs} \left(\sum_{k=1}^{n} Y_{sk} + E_{s,row} \right) \tag{6}$$

where $B = (B_{rs}) = (I - A)^{-1}$ ($GN \times GN$ matrix) is the Leontief inverse matrix (the total consumption coefficient.). According to Eqs. (3), (4), (5), and (6), the intermediate products outflow from region r to region s is divided into four parts based on the final consumption region as follow:

$$A_{rs}X_s = \underset{\text{(I)}}{A_{rs}\sum_{k \neq r} B_{sk} \sum_{l \neq i} Y_{kl}} + \underset{\text{(II)}}{A_{rs}\sum_{k=r}^{n} B_{sk}Y_{kr}} + \underset{\text{(III)}}{A_{rs}B_{sr}\sum_{k \neq r} Y_{rk}} + \underset{\text{(IV)}}{A_{rs}\sum\nolimits_{k=1}^{n} B_{sk}E_{k,row}} \tag{7}$$

From Eq. (7), term (I) represents the intermediate products outflow from region r to region s, which are used to produce final products that are consumed in regions other than region r. Term (II) represents the intermediate products used to produce final products in every region after outflow from region r to regions under the condition that final products are consumed in region r. Term (III) represents the intermediate products outflow from region r to region s to produce final products which then return to region r and are consumed in other regions. Term (IV) represents the intermediate products outflow from region r to region s to produce intermediate products which then flow to each region to produce final products that are consumed in countries or regions outside the system.

Besides, $X_r = A_{rr}X_r + Y_{rr} + E_{r^*}$, we can get:

Table 3. Total outflow decomposition of region r to region s.

Terms in accounting Eq. (12)	Decomposed value in total outflow
V1	Value-added of region *r* contained in the final products flowed from region *r* to region *s*
V2	Value-added of region *r* contained in intermediate products flowed from region *r* to region *s* but ultimately consumed in non-*r* region
V3	Value-added of region *r* contained in intermediate products flowed from region *r* to region *s* but ultimately consumed in regional *r*
V4	Value-added of region *r* contained in intermediate products flowed from region *r* to region *s* and then returned to region *r* for final product re-outflow
V5	The repeated calculation of value-added of region *r* contained in the intermediate products flowed from region *r* to region *s*
V6	Value-added of region *r* contained in the intermediate products flowed from region *r* to region *s* and then used for the production in every region for exportation to outside the system
V7	Value-added of other seven regions contained in final products flowed from regional *r* to regional *s*
V8	Value-added of other seven regions contained in intermediate products flowed from regional *r* to regional *s*
V9	Value-added double counting of other seven region

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[4] It's worth noting that the input-output table from CAS is quiet different from China Regional Input-Output Table from National Bureau of Statistics. The later can only show the input-output status of a single province, therefore, it's not suitable for building a value-added extended decomposition model.

$$A_{rs}X_s = \underset{\text{(i)}}{A_{rs}L_{ss}Y_{ss}} + \underset{\text{(ii)}}{A_{rs}L_{ss}E_{s*}} \tag{8}$$

Among them, $L_{rr} = (I - A_{rr})^{-1}$. Term (i) in Eq. (8) represents the intermediate products outflow from region r to region s, caused by region s consuming the final products produced in region s. Term (ii) represents the intermediate products outflow from region r to region s, caused by region s flow to other regions (including other regions within and outside the system).

V_r ($1 \times N$ vector) is defined as the direct added value coefficient of region r, and each element is the ratio of the added value in the region to the total output. M_r ($1 \times N$ vector) is defined as the direct import coefficient that region i imports from countries or regions outside the system. KWW (2014) assumes that there are G countries and N departments, where u represents the row vector ($1 \times N$) whose elements are all 1, then:

$$\sum_{r=1}^{n} V_r B_{rs} = u \tag{9}$$

For the reason that this study do research by using the Chinese interregional input-output table, we need to take endogenous treatment of regions outside China. Based on regional sources, the added value is divided into regions in mainland China, and countries or regions outside the system, then we can extend Eqs. (9) and (10):

$$\sum_{r=1}^{n} V_r B_{rs} + \sum_{r=1}^{n} M_r B_{rs} = u \tag{10}$$

Pan and Li (2018) decomposes the sources of added value into three parts: the added value from regions in mainland China, the added value from the Asia-Pacific and other economies, and the added value from countries or regions outside the system. This study conducts research under the logical framework of Pan and Li (2018).

According to all the above formulas, * is defined as the operation sign of multiplication of corresponding elements in the same dimension matrix at the same position. The total outflow E_{rs} of region r to region s can be expressed as:

$$\begin{aligned} E_{rs} = u^T * E_{rs} = \left(\sum_{r=1}^{n} V_r B_{rs} + \sum_{r=1}^{n} M_r B_{rs}\right)^T * (A_{rs}X_s + Y_{rs}) = \left(\sum_{r=1}^{n} V_r B_{rs}\right)^T \\ * (A_{rs}X_s + Y_{rs}) + \left(\sum_{r=1}^{n} M_r B_{rs}\right)^T * (A_{rs}X_s + Y_{rs}) \end{aligned} \tag{11}$$

Let E_{rs}^V indicate the first term on the right side of Eq. (11), and let E_{rs}^M indicate the second term. E_{rs}^V now can be decomposed into nine value-added components as follow:

$$\begin{aligned} E_{rs}^V =_{1} & (V_r B_{rr})^T * Y_{rs} +_{2} (V_r L_{rr})^T * \left(A_{rs} \sum_{k \neq r, k \in \Omega} B_{sk} \sum_{l \neq r, l \in \Omega} Y_{kl}\right) +_{3} (V_r L_{rr})^T \\ & * \left(A_{rs} \sum_{k \in \Omega} B_{sk} Y_{kr}\right) +_{4} (V_r L_{rr})^T * \left(A_{rs} B_{sk} \sum_{k \neq r, k \in \Omega} Y_{rk}\right) +_{5} (V_r B_{rr} - V_r L_{rr})^T \\ & * (A_{rs}X_s) +_{6} (V_r L_{rr})^T * \left(A_{rs} \sum_{k \in \Omega} B_{sk} E_{k,row}\right) +_{7} \left(\sum_{k \neq r, k \in \Omega} V_k B_{kr}\right)^T \\ & * Y_{rs} +_{8} \left(\sum_{k \neq r, k \in \Omega} V_k B_{kr}\right)^T * (A_{rs} L_{ss} Y_{ss}) +_{9} \left(\sum_{k \neq r, k \in \Omega} V_k B_{kr}\right)^T * (A_{rs} L_{ss} E_{s*}) \end{aligned} \tag{12}$$

The decomposition of E_{rs}^V is denoted as *V1–V9* in order, and the specific meaning is shown in Table 3.

Similarly, the second term E_{rs}^M can be decomposed into *M1–M9* as follows:

$$\begin{aligned} E_{rs}^M =_{1} & (M_r B_{rs})^T * Y_{rr} +_{2} (M_r L_{rr})^T * \left(A_{rs} \sum_{k \neq r, k \in \Omega} B_{sk} \sum_{l \neq r, l \in \Omega} Y_{kl}\right) +_{3} (M_r L_{rr})^T \\ & * \left(A_{rs} \sum_{k \in \Omega} B_{sk} Y_{kr}\right) +_{4} (M_r L_{rr})^T * \left(A_{rs} B_{sr} \sum_{k \neq r, k \in \Omega} Y_{rk}\right) +_{5} (M_r B_{rr} - M_r L_{rr})^T \\ & * (A_{rs}X_s) +_{6} (M_r L_{rr})^T * \left(A_{rs} \sum_{k \in \Omega} B_{sk} E_{k,row}\right) +_{7} \left(\sum_{k \neq r, k \in \Omega} M_k B_{kr}\right)^T \\ & * Y_{rs} +_{8} \left(\sum_{k \neq r, k \in \Omega} M_k B_{kr}\right)^T * (A_{rs} L_{ss} Y_{ss}) +_{9} \left(\sum_{k \neq r, k \in \Omega} M_k B_{kr}\right)^T * (A_{rs} L_{ss} E_{s*}) \end{aligned} \tag{13}$$

Depending on the source of value-added in Eqs. (12) and (13), the 18 items of E_{rs} are divided into five categories as shown in Table 4.

Furthermore,

$$E_{r,row}^V =_{10} (V_r B_{rr})^T * E_{r,row} +_{11} \left(\sum_{s \neq r, s \in \Omega} V_s B_{sr}\right)^T * E_{r,row} \tag{14}$$

$$E_{r,row}^M =_{10} (M_r B_{rr})^T * E_{r,row} +_{11} \left(\sum_{s \neq r, s \in \Omega} M_s B_{sr}\right)^T * E_{r,row} \tag{15}$$

In Eq. (14), $E_{r,row}^V$ is the value-added of countries or regions in the system contained in the export from region r to countries or regions outside the system. In Eq. (15), $E_{r,row}^M$ is the value-added of countries or regions outside the system contained in the exports of region r to countries or regions outside the system. V_{10} belongs to the value-added within region r, V_{11} belongs to the value-added of other seven regions in China, both M_{10} and M_{11} belong to value-added of countries or regions outside the system (RWC).

The total outflow E_{r*} of region r can be expressed as:

$$E_{r*} = \sum_{s \neq r, s \in \Omega} \left(E_{rs}^V + E_{rs}^M\right) + E_{r,row}^V + E_{r,row}^M \tag{16}$$

3.3. Trade implied carbon measurement model

Let c ($N \times 1$ vector) indicate the direct CO$_2$ emission coefficient vector, and its element $c_i^j = \theta_i^j$ represents the direct CO$_2$ emissions per unit output of department j in region i. According to Eq. (16), the total ECEs of region r based on value-added trade is as follows:

$$C_r = c_r * E_{r*} \tag{17}$$

Thus, on the basis of Eq. (17), the ECEs flowed from region r to region s (C_{rs}) and the ECEs exported from region r to countries or regions outside the system ($C_{r,row}$) can be formulated as:

$$C_{rs} = c_r * E_{rs} = c_r * \left(E_{rs}^V + E_{rs}^M\right) \tag{18}$$

$$C_{r,row} = c_r * E_{r,row} = c_r * \left(E_{r,row}^V + E_{r,row}^M\right) \tag{19}$$

Table 4. Five categories of E_{rs} decomposition.

E_{rs} decomposition in Eqs. (12) and (13)	Categories
V1, V2, V6, V10	IVA: Value-added of region r absorbed by other seven regions
V3, V11	RIV: Value-added of region r absorbed by itself
V7, V8	OVA_CHN: Value-added from other seven regions
M1–M3, M6-M8, M10, M11	RWC: Value-added from countries or regions outside the system
V4, V5, M4, M5, V9, M9	PDC: Pure double counting

Table 5. Direct CO_2 emission coefficients by region and industry.

	NE	JJ	NC	EC	SC	MR	NW	SW
Industry 1	0.156	0.322	0.108	0.191	0.132	0.165	0.220	0.153
Industry 2	0.882	0.004	0.489	0.479	0.014	0.715	0.560	0.692
Industry 3	0.290	0.305	0.331	0.077	0.260	0.210	0.426	0.418
Industry 4	1.333	0.470	0.967	0.356	0.382	1.088	2.576	1.294
Industry 5	10.376	2.249	7.823	5.670	3.899	6.781	14.309	4.207
Industry 6	0.031	0.068	0.033	0.032	0.028	0.067	0.069	0.037
Industry 7	0.672	0.295	0.521	0.325	0.458	0.658	0.940	0.906
Industry 8	0.288	0.131	0.347	0.079	0.104	0.374	0.487	0.308
All industries	1.001	0.366	0.838	0.408	0.420	0.868	1.727	0.823

Similarly, the ECEs flowed from region s to region r (C_{sr}) is expressed as:

$$C_{sr} = c_s * E_{sr} = c_s * \left(E^V_{sr} + E^M_{sr}\right) \tag{20}$$

Then, the net carbon emissions transferred from region r to region s (C^{net}_{rs}) is expressed as:

$$C^{net}_{rs} = C_{rs} - C_{sr} \tag{21}$$

4. Results and discussion

4.1. Analysis of CO_2 emission coefficients by region and industry

To obtain an accurate estimate of carbon emissions, we first calculate the total amount of CO_2 emissions from major fossil energy sources and the total output of each region. Then this section computes the direct CO_2 emission coefficients of eight major industries in eight regions of China in 2012 as per Eqs. (1) and (2). A comparison is shown in Table 5.

On the one hand, the direct CO_2 emission coefficients in regions of China are generally low in the east but high in the west, which is negatively correlated with the regional economic development level. That is, the intensity of carbon emissions in economically developed regions (such as the Beijing-Tianjin region, eastern coastal areas, and southern coastal areas)is relatively low. Conversely, regions (such as the northeast and northwest regions) with low economic development level have high carbon emission intensity. This may be related to regional industrial structure, energy structure, and energy consumption technology etc. The developed regions are dominated by low-energy-consuming industries, such as the service industry, high-end manufacturing industry, and high-tech industry. Notably, the power consumption in these regions is mainly external transmission. Therefore, the carbon emission coefficient of the whole region is significantly lower. Contrarily, the proportion of pollution-intensive industries in the northeast and northwest regions is relatively high. Similarly, coal-fired power generation, coupled with the demand for motive heating, will lead to the increase in the carbon emission coefficient. The carbon emission coefficient of five industries (electric power, steam, hot water, gas, and tap water supply) in the northeast and northwest regions almost equals five times that of the Beijing and Tianjin regions; therefore, the level of energy consumption is naturally high.

Regardless of region, five industries have the highest carbon emission coefficient, which is much higher than other industries, indicating that mining and selecting industry, production and supply of electric power, steam, hot water, gas and tap water, are high energy-consuming industries. Furthermore, the carbon emission coefficient of these five industries differs significantly among different regions, indicating the differences in energy consumption technology in different regions. The improvement of energy consumption technology can greatly reduce carbon emissions.

4.2. ECEs and transfer characteristics via inter-regional trade

Thought we have already analyzed CO_2 emission coefficients by region and industry, it can't show the dynamic transfer characteristics of

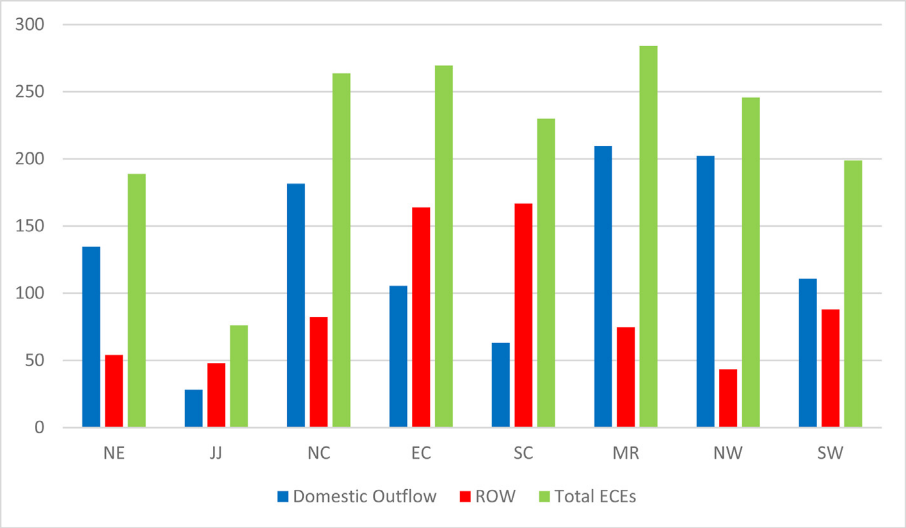

Figure 1. ECEs via value-added trade in China's eight regions in 2012 (unit: million tons). Notes: The blue part represents the total amount of ECEs from one specific domestic region to other domestic regions, the red part represents the total amount of ECEs from one specific domestic region to regions outside of China, the green part represents the total amount of ECEs from one specific region.

Table 6. Net ECEs transfer in China's inter-regional trade (unit: million tons).

	NE	JJ	NC	EC	SC	MR	NW	SW	Aggregate
NE		4.4493	−0.3688	16.6561	6.3626	9.8378	1.7586	9.6692	48.3648
JJ	−4.4493		−9.2978	−4.1262	−4.0388	−11.2895	−7.4091	−2.4598	−43.0706
NC	0.3688	9.2978		33.5181	15.3277	15.1426	−4.1874	10.6716	80.1392
EC	−16.6561	4.1262	−33.5181		0.4967	−32.9305	−42.1759	−7.7761	−128.4336
SC	−6.3626	4.0388	−15.3277	−0.4967		−8.1028	−8.0919	0.4489	−33.8941
MR	−9.8378	11.2895	−15.1426	32.9305	8.1028		−14.7078	0.3571	12.9916
NW	−1.7586	7.4091	4.1874	42.1759	8.0919	14.7078		10.3016	85.1152
SW	−9.6692	2.4598	−10.6716	7.7761	−0.4489	−0.3571	−10.3016		−21.2125

China's domestic emissions. Therefore, we further focus on the ECEs and carbon emission transfer characteristics of the inter-regional value-added trade following Eqs. (18) and (19), respectively. By calculating the ECEs of value-added trade in eight regions of China, we find that the central region (284.1972 million tons), eastern coastal region (269.53.89 million tons), and the northern region (263.7032 million tons) have the highest emissions. The high carbon emissions in the central region are mainly due to the high intensity of carbon emissions, while the high carbon emissions in the eastern and northern coasts are due to the large economic aggregate. The ECEs outflow in the Beijing-Tianjin region is the minimum, the reason why is that the dual effect of low carbon emission intensity and small economic aggregate.

Figure 1 shows three main results. First, in 2012, the total ECEs of China's domestic inter-regional value-added trade is 1035.65 million tons, much higher than the total ECEs of its value-added trade with foreign countries of 721.15 million tons. The finding confirm that the domestic inter-regional trade remains the main form of trade and the carbon emission intensity of China's export commodities is relatively low. For example, the products produced in the Beijing-Tianjin region, the eastern coast, and the southern coast, are mainly used for the further processing and production of foreign downstream producers. Moreover, these three regions have few energy-consuming industries and low carbon emission intensity. Second, the northern coast, the eastern coast, the central region, and the northwest region have higher total ECEs from value-added trade of domestic inter-regional trade, at 263.7 million tons, 269.53 million tons, 284.19 million tons, and 245.75 million tons, respectively. Moreover, the Beijing-Tianjin region, the eastern coastal region, and the southern coastal region are export-oriented economies. Therefore, ECEs of thees three regions in domestic inter-regional outflow are significantly lower than in foreign exports. Conversely, the added value created by the north, central, and northwest regions is mainly supplied for production in other regions of China. Therefore, ECEs flowed to other regions in China are significantly greater than that exported to foreign countries, of which the implied carbon in the export to foreign countries in the northwest region only accounts for 18% of the total outflow. Third, geographical location significantly influences the transfer

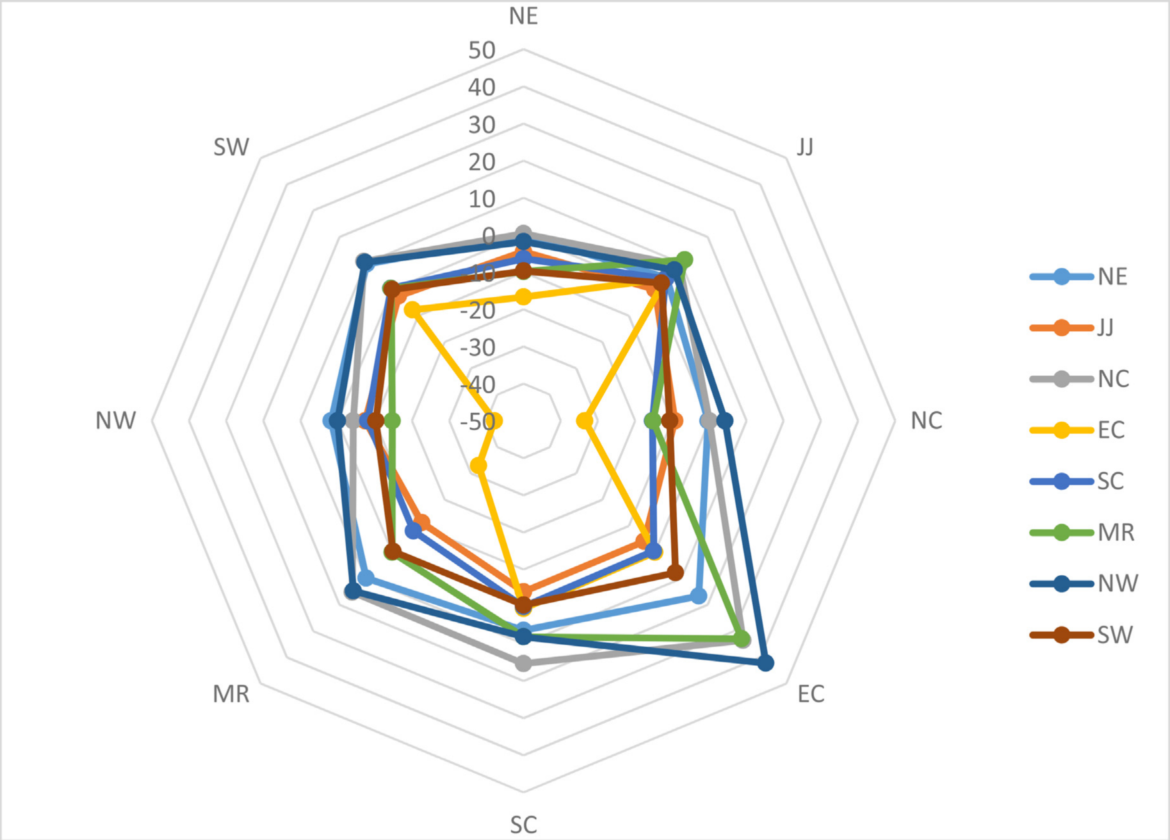

Figure 2. Net ECEs transfer in China's inter-regional trade (unit: million tons). Note: The negative value represents net ECEs inflow amount, the positive value represents net ECEs outflow amount.

of ECEs between regions. As China's transportation hub and economic hinterland, the central region has large-scale commodity circulation with other regions. It ranks first in terms of the outflow of ECEs to other regions, but second only to the east coast in terms of inflow of ECEs from other regions. As for coastal areas, the northern coastal areas mainly meet domestic demand, while the eastern and southern coastal areas are oriented to foreign markets. The reason is that, on the one hand, the eastern and southern coastal areas began modernization earlier and lead in many areas of reform and opening-up, with a higher level of opening-up. On the other hand, the northern coastal areas lie in the northern part of the North China Plain, with vast hinterland, radiating to the northeast, central, and other regions.

According to Eqs. (20) and (21), we can calculate the net ECEs transfer in China's inter-regional trade and the total net ECEs outflow of each region. For the sake of brevity, Table 6 and Figure 2 show the net value of CO_2 transfer implied in the value-added trade of the eight regions in detail. The northeastern region, the northern coastal region, the central region and the northwest region are the net carbon outflow regions, that is, the trade implied CO_2 emission outflow is greater than the CO_2 emission inflow. The northwest region is the largest net carbon outflow region, moreover, its value-added trade with the other six regions, except the northeast region, is in the net carbon outflow state. The causes of this phenomenon are multiple. On the one hand, there is carbon leakage from economically developed regions to economically underdeveloped regions in China, and the products produced in the underdeveloped regions are mostly used to provide intermediate and final products to other regions in China. On the other hand, ECEs outflow of the northwest region is closely related to its industrial structure. Northwest China is rich in natural resources such as gas and minerals, moreover, it has a large proportion of pollution-intensive industries. Therefore, this region has a high carbon emission coefficient and a large amount of ECEs outflow. As for the northern coastal region, it is a strong economic hinterland of China with rich natural resources and convenient transportation. Therefore, the northern coastal region is also in the net carbon outflow state in trading with six other regions, except the northwest region. However, the eastern coastal region is the largest net carbon inflow region, with a net carbon inflow of 128.4336 million tons, among which the carbon inflow from the northern coastal region, the central region, and the northwest region is relatively high, at 33.5181 million tons, 32.9305 million tons, and 42.1759 million tons, respectively. In addition, the Beijing-Tianjin region is in the carbon inflow state when trading with seven other regions. Generally, the ECEs in value-added trade is transferred from inland to coastal areas in China.

From the net value of ECEs inflow by the value-added trade, we find that the eastern coastal region ranks first, with about 128 million tons of net carbon inflows. The large-scale demand for domestic commodities makes the eastern coastal region put the greatest impact on ECEs outflow from other regions. The Beijing-Tianjin region which is small and is not rich in fossil energy also has a huge amount of net ECEs inflow. In this region, the high-tech industry is intensive, the economy is developed, and the power consumption is mainly external transmission. Therefore, the region needs a large number of intermediate products from other regions to meet its own production demand, then the amount of ESEs inflow with trade is higher. One interesting phenomenon is that the net ECEs inflow volume of the eastern coastal region and the Beijing-Tianjin region (128.4336 million tons, 43.0706 million tons) is actually lower than the total ECEs outflow of the two regions to foreign countries (164.0375 million tons, 478.429 million tons). This again proves that the products produced in this region are mainly exported to foreign countries.

5. Conclusions and policy recommendations

Based on the input-output table of eight sectors in eight regions of China in 2012, this study uses the value-added trade accounting method based on input-output technology to calculate the implied carbon emissions and transfers of value-added export trade among these eight regions of China. The main conclusions are as follows: in 2012, the northern coastal, eastern coastal, central, and northwestern regions have higher implied carbon emissions from China's domestic inter-regional exports. Among them, the high direct CO_2 emission coefficient is an important reason for the high carbon emissions in the northern coastal, central, and northwestern regions. In addition, the Beijing-Tianjin region, the eastern coastal region, and the southern coastal region are export-oriented economies. Therefore, the trade implied carbon of these three regions to domestic inter-regional exports is significantly less than that to foreign exports. In terms of net carbon transfer value, the northeast, north coast, central, and northwest regions are net carbon transferring out regions, while the rest regions are net carbon transferring into regions. Within China, the implied carbon in value-added trade shifts from inland to coastal areas along with commodity exports. Not only is the net value of China's inter-regional carbon emission transfer affected by the direct carbon emission coefficient, it is also closely related to the regional industrial structure.

Based on the empirical findings, this study conveys some policy implications. First, China should accelerate the improvement in technological innovation capacity in less developed areas, develop energy-saving technologies, promote the optimization and upgrading of industrial structure, and eliminate backward production capacity. This is the only way to eliminate high-polluting and high energy-consuming industries, reduce the direct CO_2 emission coefficient, and fundamentally reduce CO_2 emissions. Second, it is important to seek more reasonable implicit carbon measurement methods, such as using value-added trade statistics to eliminate duplicated accounts, and establish a reasonable regional carbon emission sharing mechanism. Third, considering the full launch of China's carbon emissions trading market, in terms of regional quota allocation, we should scientifically determine the quota allocation scheme according to the historical emission list, the characteristics of industrial structure, and the stage of economic development. Furthermore, it is necessary to improve the carbon emission market trading system and scientifically allocate carbon emission quota between regions with different emission reduction costs through the price mechanism. This is the only way to eliminate the inequity of inter-regional carbon emission rights and responsibilities, and improve the overall efficiency of carbon emission reduction, which has important application value in achieving China's goals of reducing carbon emission.

Due to the limitation of statistical data, this study fails to analyze the ECEs of value-added trade between China's regions and the rest of the world. If we can locate the position of each region in the global value chain, it will provide a new idea for China to implement the carbon emission reduction policy. In addition, the data also has a limitation for lacking timeliness. The possible reason is that the preparation of an input-output table consumes much manpower and hours to do data collection and processing.

Declarations

Author contribution statement

Chenyang Ran: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper. Xueliu Xu: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper. Songzi Zhang: Analyzed and interpreted the data; Wrote the paper.

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Data availability statement

Data associated with this study has been deposited at National Bureau of Statistics of China under the accession number ISBN 978-7-5037-8452-1.

Declaration of interest's statement

The authors declare no conflict of interest.

Additional information

No additional information.

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