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Worsening Carbon Inequality Embodied in Trade within China

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DOI:
10.1021/acs.est.2c05990

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Document Version
Peer reviewed version

Citation for published version (Harvard):
Zhang, H, Zhang, W, Lu, Y, Wang, Y, Shan, Y, Ping, L, Li, H, Lee, LC, Wang, T, Liang, C, Jiang, H & Cao, D 2023, 'Worsening Carbon Inequality Embodied in Trade within China', *Environmental Science and Technology*, vol. 57, no. 2, pp. 863-873. https://doi.org/10.1021/acs.est.2c05990

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Download date: 02. May. 2024

Worsening carbon inequality embodied in trade within China

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Abstract:

The mismatch between trade-embodied economic benefits and CO_2 emissions causes carbon inequality, which is seldom analysed from intra-country level, especially across a long-term period. This study applied an environmentally extended multi-regional input-output model to trace this mismatch and measure the carbon inequality quantitatively within China during 2007-2017. The results show that during the past decade, China's national carbon inequality was continuously worsening with carbon Gini coefficients rising regardless of production- (0.21-0.30) or consumption-based (0.12-0.18) accounting. The regional carbon inequality was deteriorating, where less developed provinces with 20% of total value-added emitted 32.9% of total CO_2 emissions in 2007, while this figure rose to 42.6% in 2017. The eastern provinces (Jiangsu and Shanghai) had entered into net economic and carbon beneficiaries keeping high trade advantages, by contrast the northwest provinces (Ningxia and Xinjiang) were trapped in a lose-lose situation with trade benefits declined 68%. The southwest provinces (Yunnan and Guangxi) shifted from being net carbon & value-added exporters to net importers, stepping into the earlier development mode of eastern provinces. This hidden and exacerbated carbon inequality calls for regional-specific measures to avoid the dilemma of economic development and CO_2 mitigation, which also gives a good reminder for the rising economies, like India.

Keywords: Trade-embodied CO_2 emissions; Value-added; Multi-regional input–output analysis; Carbon inequality; Gini

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coefficient; Emission terms of trade

Synopsis: Minimal research reveals the carbon inequality based on trade-embodied CO_2 and value-added, especially from a long-term period. This study reports a continuously worsening carbon inequality embodied in trade within China during 2007-2017 with mitigation suggestions.

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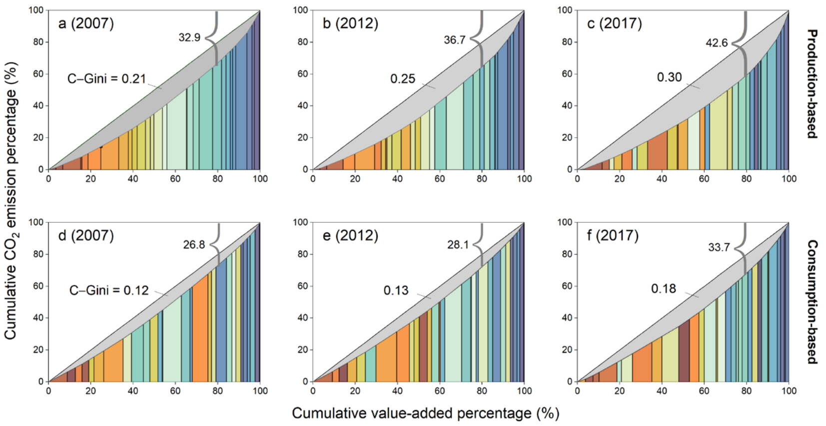

1. Introduction

The good living standard of developed countries comes at the expense of large CO_2 emissions produced in less affluent, developing countries[1, 2, 3, 4, 5, 6]. A similar phenomenon also happens among regions within a country, especially in China, which is a vast country with great regional variations in economic development, resource endowments, population and lifestyle[7,8]. To accelerate the economic growth in less developed western China, the Western Development Strategy was launched by the Chinese government in 2000, with a large investment in infrastructure, natural resources exploitation and industry transfer (mainly energy-intensive industries) from the East[9]. As a result, the Gross Domestic Product (GDP) of 12 provinces in the west region had indeed increased 12.7 times between 1999 and 2019, with an average economic growth of 10.9% annually, higher than the national level of 8.9%[10]. However, the development of energy-intensive industries (i.e., coal power plants, cement, coal chemicals) in west provinces brought not only economic benefits but also lead to huge CO_2 emissions locally[11]. What's worse, the transferred industries from the eastern provinces with stringent low carbon and energy-saving policies may release more CO_2 after moving to the west with lenient regulations, leading to an extra increase in CO_2 emission on the national scale[12]. Thus through trade within China, affluent East China imports the low value-added but high carbon-intensive products from less developed Middle and West China, and exports the high value-added but low carbon-intensive products in reverse, which leads to unbalanced CO_2 emissions and value-added transfer in the trade process and triggers the regional/provincial carbon inequality[7, 13, 14, 15].

Carbon inequality was previously neglected by China's local governments as no strict regulations were implemented on the carbon issue. However, after signing the Paris Agreement in 2015, the responsibility of carbon embodied in trade attracted more attention[16]. Especially, in 2020, China pledged to reach peak carbon dioxide emissions by 2030 and achieve carbon neutrality (net-zero emissions) by 2060. Later on, China committed to reducing the carbon intensity of its economy [i.e., CO_2 emissions per unit of gross domestic product (GDP)] by 65% from 2005 levels and to generating about 25% of its primary energy from non-fossil sources by 2030[17]. Facing stricter carbon mitigation pressure, provinces may complain that part of the territorial CO_2 emissions was caused by other provinces' consumption through trade and should not be responsible for that part of emissions. For example, 52 percent of CO_2 emissions caused by Beijing's consumption are outsourced by other provinces[8]. Thus policies regarding CO_2 emissions embodied in trade become quite essential to avoid the dilemma of economic growth and CO_2 mitigation, especially for the less developed western provinces [18].

To tackle the carbon inequality embodied in trade, consumption-based instead of production-based CO_2 emission counting was advocated by scholars [19, 20, 21]. As final demands (consumption included) are the real drivers for producing high carbon-intensive products, consumers should be responsible for the CO_2 emissions during production. Thus, the carbon inequality issue should be analyzed based on a consumption perspective. Based on that, plenty of studies revealed the CO_2 transfer quantity and directions embodied in trade from both national scale [22, 23, 24, 25, 26] and sub-national scale[15, 27, 28, 29]. However, as a key factor in the trade process, the economic gain (value-added) was seldom analyzed accompanied with carbon transfer [8, 30]. The inequality issue has also been quantitatively measured using multiple approaches. Wang et al.[23] constructed an environmental inequality indicator similar as Pollution Terms of Trade (PTT) to examine the change of economic benefits and sulfur dioxide emissions underlying China's international trade from 2002 to 2015. Mi et al.[9] utilized Gini coefficient to explore the inequality change between household carbon footprint and income, and found that carbon inequality declined with economic growth in China during 2007-2012, which was a positive result. Similarly Xu's study revealed that per capita CO_2 emissions inequality also showed a downward trend during 2003-2015 using the Theil index[31]. However, as far as we know, no studies explored the carbon inequality changes based on trade-embodied CO_2 emissions and value-added, especially from a long-term period within China. With fast economic growth and deep industry structure adjustment during the last decade, the types of goods embodied in trade have changed largely among provinces in China, which affects the carbon and value-added transfer and makes it necessary to operate a long-term analysis to observe the regional/provincial carbon inequality changes within China[27].

In this study, we firstly constructed the latest environmental extended MRIO tables of 2007, 2012 and 2017 to calculate the regional and provincial CO_2 emissions as well as value-added embodied in China's inter-regional trade from both consumption and production sides. Then we traced the trend in the net transfer of embodied CO_2 emissions and value-added among regions. At last, we further applied the carbon Gini (C-Gini) coefficient and emission terms of trade (ETT) indicator simultaneously to reveal the changes in carbon inequality induced by inter-regional trade. Noting that in order to better reflect the situation within China, we only focused on domestic investment and consumption, and removed the export-driven effect. We found that China's national carbon inequality was continuously worsening during 2007-2017, which was a bad news and a different result with previous studies[9, 31]. Regional disparity kept deteriorating, where the eastern provinces (Jiangsu and Shanghai) shifted to both net economic and carbon beneficiaries in 2017, while northwestern provinces (Ningxia and Xinjiang) were trapped in both net economic and carbon losers. These interesting results featuring regional disparity will help decision-makers to seek region-specific solutions for CO_2 emission mitigation and economic development.

2. Methods

2.1 Environmentally extended input-output analysis

An environmentally extended multi-regional input-output (MRIO) model was used in this study to estimate provincial and regional carbon transfer embodied in trade within China from 2007 to 2017. The input-output analysis is widely used to describes the economic linkages among different economic sectors based on input-output tables, especially for MRIO analysis, which can further reflect the inter-regional trade of commodities and services[32, 33, 34]. Based on that, environmental extended MRIO analysis was well developed to further examine the trade-related air pollution[35, 30], carbon dioxide[24, 36], water[37, 38], land use[39, 40], energy use[41], material use[42, 43] and health impacts[44, 45]. The basic linear equation of MRIO analysis is:

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

$$X = \begin{bmatrix} x^1 \\ x^2 \\ \vdots \\ x^n \end{bmatrix}, A = \begin{bmatrix} a^{11} & a^{12} & \cdots & a^{1n} \\ a^{21} & a^{22} & \cdots & a^{2n} \\ \vdots & \vdots & \vdots & \vdots \\ a^{n1} & a^{n2} & \cdots & a^{nn} \end{bmatrix}, F = \begin{bmatrix} f^{11} & f^{12} & \cdots & f^{1n} \\ f^{21} & f^{22} & \cdots & f^{2n} \\ \vdots & \vdots & \vdots & \vdots \\ f^{n1} & f^{n2} & \cdots & f^{nn} \end{bmatrix} \tag{2}$$

where X is the vector of total economic outputs (x_i^r) and x_i^r is the total output of sector i in region r. A is the direct consumption coefficient matrix (a_{ij}^{rs}), derived by $a_{ij}^{rs} = z_{ij}^{rs}/x_j^s$, in which z_{ij}^{rs} represents the intersectoral monetary flows from sector i in region r to sector j in region s, and x_j^s is the total economic output of sector j in region s. I is the identity matrix and $(I - A)^{-1}$ is the Leontief inverse matrix. F is the final demand matrix containing f_i^{rs}, which is the final demand of region s for the goods of sector i from region r. In this study, the export demand is removed for domestic trade analysis. The final demands only contain investment (fixed capital formation) and consumption from individuals and government.

To calculate the CO_2 emissions (C) and economic benefits (W) embodied in trade within China, the environmental extended MRIO tables are used on the basis of carbon intensity (K, CO_2 emissions per unit of economic output) and value-added intensity (V, value-added per unit of economic output), following by the equations:

$$C = K(I - A)^{-1}F \tag{3}$$

$$W = V(I - A)^{-1}F \tag{4}$$

where C is the total CO_2 emission and W is the total value-added. Then the production-based CO_2 emissions C_p^r and economic benefits W_p^r in a specific region r driven by national consumption can be expressed as follows:

$$C_p^r = K^r(I-A)^{-1}F \tag{5}$$

$$W_p^r = V^r(I-A)^{-1}F \tag{6}$$

By contrast, the consumption-based CO$_2$ emissions C_c^r and economic benefits W_c^r in region r driven by its own consumption can be expressed as follows:

$$C_c^r = K(I-A)^{-1}F^r \tag{7}$$

$$W_c^r = V(I-A)^{-1}F^r \tag{8}$$

The production-based CO$_2$ emissions intensity (PBEI) I_p^r and the consumption-based CO$_2$ emissions intensity (CBEI) I_c^r in region r are calculated by the following equations:

$$I_p^r = C_p^r / W_p^r \tag{9}$$

$$I_c^r = C_c^r / W_c^r \tag{10}$$

While the CO$_2$ emissions C^{rs} and economic benefits W^{rs} in region r driven by final demand from s can be written as follows:

$$C^{rs} = K^r(I-A)^{-1}F^s \tag{11}$$

$$W^{rs} = V^r(I-A)^{-1}F^s \tag{12}$$

The net CO$_2$ emissions and economic benefits of region r can be expressed as follows：

$$NetC^r = C^{rs} - C^{sr} \tag{13}$$

$$NetW^r = W^{rs} - W^{sr} \tag{14}$$

2.2 Emission Terms of Trade (ETT) indicator

The ETT indicator was evolved from the concept of PTT appeared in introduction part, where we replaced “Pollution” with “Emission” as CO$_2$ isn’t a pollutant. This indicator was first proposed by Antweiler in 1996 to quantify the environmental gains and losses induced by different countries in international trade[46]. As the indicator can indicate the trade imbalance caused by the import and export volume change, and can be used as a long-term measurement of ecologically unequal exchange, it become prevalent in the related fields. Here, the ETT indicator of a province or a region was calculated to characterize the interaction between economic benefits and CO$_2$ emissions embodied in trade within China as expressed by Eq. (15).

$$ETT_r = \frac{1}{n}\sum_{s=1}^{n}\frac{C^{rs}/W^{rs}}{C^{sr}/W^{sr}} \tag{15}$$

where C^{rs} and W^{rs} represents the CO_2 emissions and economic benefits in a specific region r driven by final demand from region s $(r \neq s)$. For the provincial ETT values, n equals to 29, representing trade between one province with the other 29 provinces; For the regional ETT values, n equals to 7, representing trade between one region with the other 7 regions. If the ETT indicator is larger than one, it means that exports of region are dirtier than its import. Therefore, the higher the value of ETT, the more inequalities the region bear from trade within China.

2.3 Carbon Gini coefficient

In order to reveal China's carbon inequality change during the period of 2007-2017, the production-based and consumption-based carbon-footprint-Gini coefficients were constructed based on the well-known Gini coefficient, which is derived from Lorenz curves, proposed by the Italian economist Corrado Gini to determine quantitatively the level of difference in the income distribution, and now widely used to measure inequality[47, 48, 49, 50, 51]. The original Lorenz curve plots population shares against income shares, where the area below that curve is defined as Gini coefficient, ranging from 0 to 1. A straight 45° line in the Lorenz curves would indicate perfect equality; similarly, a Gini coefficient of 0 indicates perfect equality, and 1 indicates perfect inequality[52]. The basic income Gini coefficient of China is calculated by:

$$G = \sum_{i=1}^{n} D_i Y_i + 2 \sum_{i=1}^{n} D_i (1 - T_i) - 1 \tag{16}$$

where G refers to the Gini coefficient, D_i and Y_i are the proportions of the population and income of each province, respectively. T_i represents the cumulative proportion of the income of each province, and i $(i = 1, 2, 3, \ldots, n)$ refers to the number of provinces[9]. In our study, 30 provinces of China are included due to data availability. At the same time, we have replaced the income with carbon emissions and the population with value-added in order to calculate carbon-related Gini (C-Gini) coefficient based on trade-induced value-added. The C-Gini coefficients of China for 2007, 2012 and 2017 are all calculated from both production- and consumption-based perspectives.

2.4 Data sources

The 2007 China MRIO table is compiled by the Development Research Center of the State Council of China[53, 54], which covers 30 provinces (except Tibet) of the main land China and 37 industrial sectors. The 2012 and 2017 China MRIO tables are taken from the CEADS database[55], which consists of 42 industrial sectors and 31 provinces of China. In order for better comparison of changes during 2007 and 2017, the 37 or 42 sectors are aggregated into 8 sectors as shown in Supplementary Table S1-S3, and 30 provinces of China are included in this study, which are also aggregated into 8 regions for regional analysis, shown in Supplementary Table S4.

The energy consumption and emission factors are needed to calculate CO_2 emission inventories for the 30 provinces. The energy consumption data can be obtained from the China Energy Statistical Yearbooks[56]. The CO_2 emission factors can be also obtained from the CEADS database[57], which is more localized than the values calculated by IPCC default values. Studies has shown that these default emission factors overestimate China's carbon emissions[58]. However, China's coal contains high ash content and low carbon content compared with the samples of coal mines provided by IPCC, based on research of 602 coal samples on site from the 100 largest coal-mining areas in China.

3. Results

3.1 Production- and consumption-based CO_2 emissions for regions and provinces during 2007-2017

The total production- or consumption-based CO_2 emissions within China changed from 5037 to 8058 million tons (Mt), about 60.0% increase during the last decade from 2007 to 2017 (Supplementary Table S5), with a fast growth between 2007 to 2012 (8.1% per year) and a relatively low growth between 2012 to 2017 (1.6% per year). As shown in Fig.1, consumption-based CO_2 emissions of the affluent and developed regions (i.e., East Coast, South Coast and Beijing-Tianjin) were usually higher than that of production-based with emission ratio of consumption/production higher than 1. By contrast, the consumption-based CO_2 emissions are relatively lower than that of production-based in less affluent regions (Northwest, Northeast and North), where heavy industries are basically rooted, with emission ratio lower than 1. While from the production-based accounting, the emission of the Northwest region grew fastest, changing from the fourth largest (618Mt) in 2007 to the second largest (1456Mt) in 2017, showing that fossil fuels were largely consumed locally. Regarding the consumption-based emissions, it's worth noting that the Southwest region showed a strong increase in consumption-based emissions, reaching the second largest (1246Mt, 15.5% of the total emissions) in 2017 compared with the fourth (955Mt, 12.9%) in 2012, which was probably driven by strong investment. Yunnan and Guizhou province of Southwest region in China have almost similar development stage and their emission ratios were both lower than 1 in 2007. The consumption emissions of these two southwestern provinces have increased significantly, and their ratios of consumption/production have also risen in 2017. Especially, the consumption-based emissions of Yunnan have been significantly higher than the production-based emissions (i.e. the ratio is higher than 1), reaching a similar position with the eastern coastal provinces. Therefore, it is necessary to pay more attention to the changes in southwest provinces. Compared with CO_2 emissions, the trade-induced value-added also experienced similar trend during the past decade as shown and explained in Supplementary Table S6.

From the sector level (Fig.1), Electricity production, and Heavy industry were the leading production-based emission sectors where coal-based energy was consumed directly by industries and CO_2 emissions were released. These two sectors took up to 82.7% of the total production-based emissions in 2007 and almost kept the same pace, with 82.5% in 2012 and 82.9% in 2017. The service industry followed behind and showed a slight increase in CO_2 emission percentage during the last decade, which were 8.7% (2007), 9.6% (2012) and 10.3% (2017), respectively. While the consumption-based emissions were mainly triggered by Construction, Service and Heavy industry, together taking up more than 80% of the total emissions. The Construction sector always took the leading position, increasing from 38% in 2007 to 46% in 2017, which was mainly due to the growth of the construction industry driven by China's urbanization process and huge investment in infrastructure. This sector accounted 64.6%-72.8% emissions led by Investment (Supplementary Fig.S1). The Service sector took up about 20% emissions, ranking the second largest due to its close relationship with our daily life, which dominated the emissions (43.5%-46.9%) led by Household and Governmental Consumption. While the Heavy industry sector also possessed more than 20% of the total emissions during 2007-2012, which can be explained by its second largest emitter of investment-induced emissions, and then decrease to 16% of the total in 2017 as China's green industrial transition.

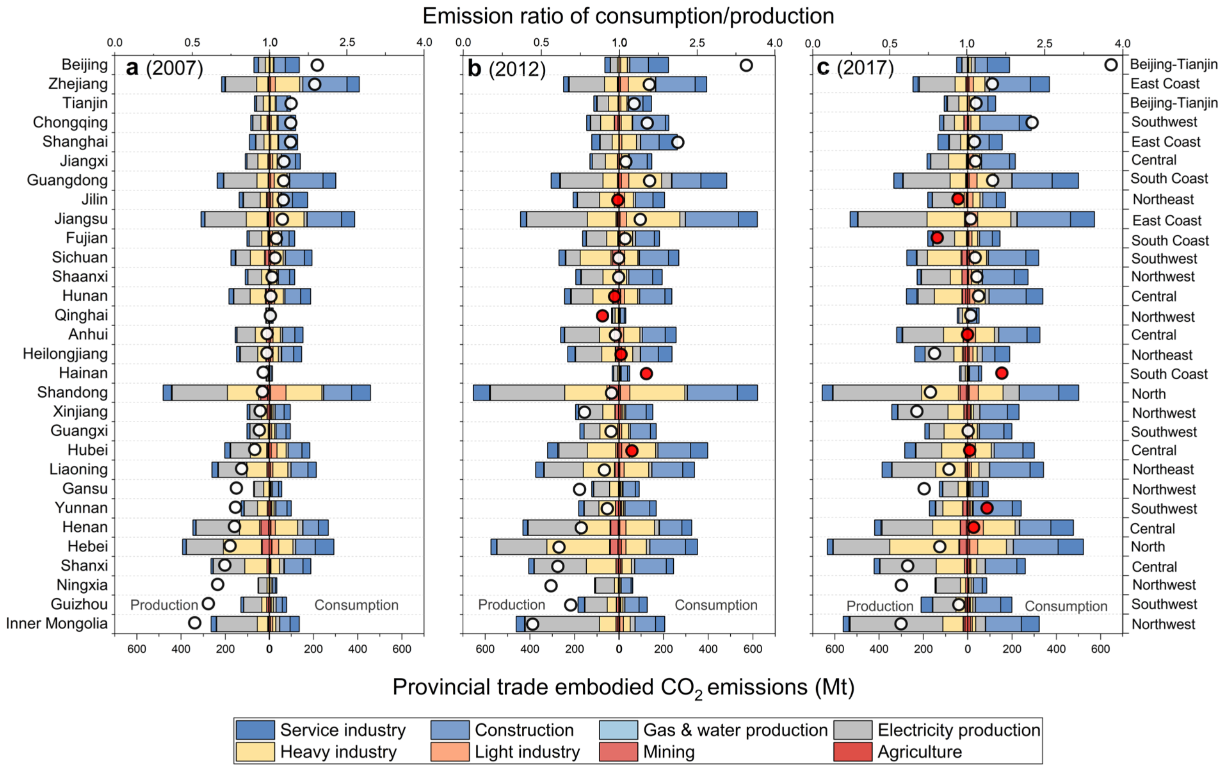

Figure 1 | Comparison of provincial CO_2 emissions from production and consumption perspectives. The production-based and consumption-based CO_2 emissions by province are illustrated on the left and right respectively from 2007 to 2017. The production- or consumption-based part is composed of eight sectors, including Agriculture, Mining, Light industry, Heavy industry, Electricity production, Gas & water production, Construction and Service industry. The 30 provinces (left vertical axis) are divided into 8 regions (right vertical axis) for better analysis, where Beijing-Tianjin refer to Beijing and Tianjin, North refer to Hebei and Shandong, Northeast refer to Liaoning, Jilin and Heilongjiang, East Coast refer to Shanghai, Jiangsu and Zhejiang, Central refer to Shanxi, Anhui, Jiangxi, Henan, Hubei and Hunan, South Coast refer to Fujian, Guangdong and Hainan, Southwest refer to Guangxi, Chongqing, Sichuan, Guizhou and Yunnan, Northwest refer to Inner Mongolia, Shaanxi, Gansu, Qinghai, Ningxia and Xinjiang. The bubble indicates the emission ratio of consumption-based divided by production-based, where the red bubbles mean direction changed compared with 2007. Mt means million tons.

From the carbon intensity perspective, in which we utilized the CO_2 emissions divided by value-added gains, the average national carbon intensity (CI) increased first, from 2.4 t/ten thousand yuan (Chinese currency, 1 yuan equals to 0.13 dollar of year 2007) in 2007 to 2.7 t/ten thousand yuan in 2012, and then dropped to 2.6 t/ten thousand yuan in 2017 regardless of production- or consumption-based accounting (Supplementary Fig.S2). It seems there were no substantial changes for China's national CI, however, the provincial CI vary largely, especially for production-based accounting. From the production view, the production-based emission intensity (PBEI) of affluent eastern and southern provinces was relatively lower than that of less-developed central and western provinces. Besides, the PBEI kept still or little changes with times flown during 2007-2017, such as Jiangsu (from 1.7 to 1.8), Guangdong (from 1.7 to 1.8) and Fujian (from 1.6 to 1.5). On the contrary, in Western provinces, especially in the Northwest region, such as Inner Mongolia (from 5.0 to

8.9), Xinjiang (from 3.4 to 7.3) and Gansu (from 3.2 to 4.0), the PBEI were enlarging, leading to wider provincial difference from the national scale. From the consumption view, the consumption-based emission intensity (CBEI) increased for almost all provinces during 2007-2012, showing a need for high carbon products for daily life, which also corresponded to the quick improvement of people's living standards during that period. After that, affluent eastern provinces tend to green consumption under strict regulations (e.g., mobile car purchasing and driving limitation, renewable energy usage), leading to low CBEI during 2012-2017, such as Jiangsu (from 2.3 to 2.0), Shanghai (from 2.5 to 1.7) and Fujian (from 2.0 to 1.3). While due to easy access to fossil fuels and a strong wish for a better life, the less developed western provinces kept consumption of high carbon products (e.g., purchasing mobile cars, and household appliances), making CBEI increase continually, such as Inner Mongolia (from 4.0 to 5.6), Ningxia (from 5.1 to 5.3) and Xinjiang (from 4.3 to 4.8), thus leading to polarized CI nationwide too.

3.2 Net flows of CO_2 emissions and economic benefits embodied in trade

In this study, the net emission of a region equals to the import-induced emission minus the export-induced emission between trade with other regions within China, where the positive value means the net inflow of CO_2 emission and the negative value represents the net outflow of emission. From the net CO_2 emission flows (Fig.2), we can tell that the net CO_2 outflow regions lie in relatively less developed western and middle areas where the production-based emissions are high while the consumption-based emissions are relatively low. It is worth noting that the net emission inflow of the East coast region decreased from 460Mt in 2012 to 183Mt in 2017 (Supplementary Table S7); the reason is that due to the CBEI decrease (Supplementary Fig.S2), despite the consumption volume kept little change (from 5412 billion to 5354 billion, constant price), the consumption-based emissions of this region declined (from 1275 Mt to 1096Mt) during 2012-2017, while the production-based emissions continued rising (Fig.1b-c). The largest change happens in the Southwest and Central regions, which shifted from net emission exporters to net emission importers (Fig.2a-c), and the flow change rates between Southwest/Central and other regions are quite high (Supplementary Table S8). The net CO_2 emissions of Southwest changed from -33Mt in 2007 to 267Mt in 2017, while this figure changed from -124Mt to 10Mt for Central. This is probably led by the vast investment and improvement of people's living standards in these regions, leading to a quick increase in consumption-based emissions, which surpassed that of production-based in 2017 as shown in Fig.1a-c.

Trade is driven by profit. When inter-regional trade happens, it not only causes the embodied CO_2 emission flow but also brings economic benefit. In this study, we have also calculated the net value-added flow for a region, which is equal to value-added loss from import minus value-added gain from export. The positive value means net value-added inflow, while the negative value means net value-added outflow. As we can see from Fig.2d and e, the net value-added outflow regions lay also in the middle and west, as well as in the Northeast, which was corresponding with the CO_2 net outflow regions, showing that these regions emitted large CO_2 emissions to satisfy developed regions' consumption but at the same time gained some economic benefit as compensation during 2007-2012. The largest net value-added inflow lies in the East coast region (Fig.2d) in 2007, with a figure of 391 million and this figure increases to 421 million in 2012 (Fig.2e and Supplementary Table S9). However, huge changes happened in 2017 (Fig.2f). First, the East coast became the net value-added outflow region, even though the net carbon emissions of this region was still inflow, showing that the East coast region not only gains economic benefits but also carbon benefit through trade. Second, although the net carbon flow was still directed from Central and West to East, the net value-added flow had shifted directions from Central and East to Southwest. What's more, most of the net value-added flows between Northwest and other regions became weak (Supplementary Table S10 and Fig.S4); the Northwest region gained little net value-added, while the carbon loss was still huge. The inconsistency of carbon and value-added flow showed great inequality embodied in trade within China.

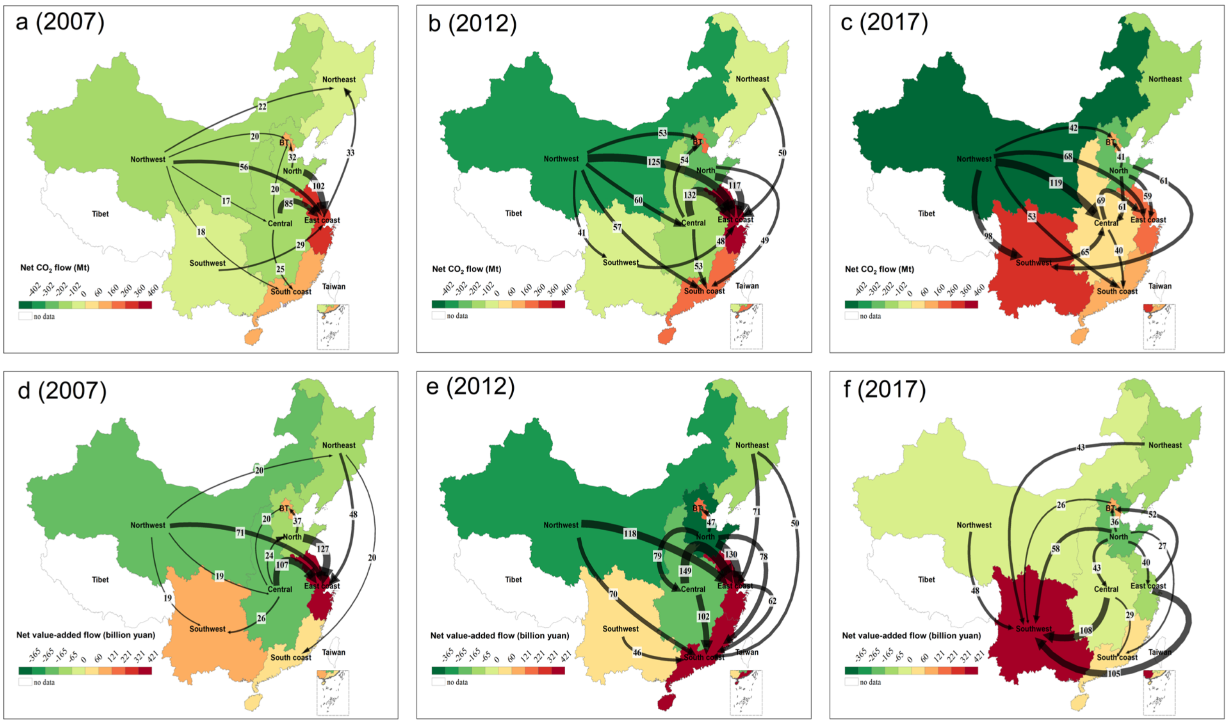

Figure 2 | Changes in emission and value-added patterns within China. The greener the colour is, the higher the net outflow value means; The redder the colour is, the higher the net inflow value represents. **a** Net emission flows in 2007, **b** Net emission flows in 2012, **c** Net emission flows in 2017, **d** Net value-added flows in 2007, **e** Net value-added flows in 2012, **f** Net value-added flows in 2017. Only 12 biggest net flows are chosen and showed for each figure. Mt means million tons. BT is short for Beijing-Tijian.

3.3 Grouping and ETT changes for regions and provinces

To investigate the inequality distribution among regions and provinces, first, we classified the regions or provinces into four groups according to the positive or negative values of net value-added and CO$_2$ emissions embodied in trade. As shown in Fig.3, generally most of the affluent regions, such as Beijing-Tianjin, East coast and South coast, are located in the Group I (the upper right-hand quadrant), which indicates that these regions are carbon winners (positive in their net CO$_2$ emission transfer) and economic loser (positive in their net value-added output). For example, in 2007, one unit of value-add (yuan) export from the East coast region to other regions will bring 251g CO$_2$ emissions locally, but it will lead to 431g emissions for other regions (per yuan) due to East region's import. The less-developed regions, such as North, Northeast, Northwest, are located in Group III (the lower left-hand quadrant), showing that these regions are carbon loser (negative in their net CO_2 emission transfer) but economic winner (negative in their net value-added output) through trade within China. This is relatively fair for regions in Group I and III, as they gain either economic benefits with a carbon emission loss or carbon rewards (less carbon emission) with economic cost. However, this balance broke down by the East region in 2017 (Fig.3c). As East region become both economic winner (126-billion-yuan net value-added income) and carbon winner (net 184Mt emission output), which shows large inequality happens when trading between the East coast region and other regions of China.

Then, the ETT indicator is utilized to further explore the trade-related inequality quantitatively within China. Basically, the low ETT values are carbon winner & economic loser (Group I), and regions with high ETT values are carbon loser & economic winner (Group III). From the regional perspective, there were five out of eight regions with values higher than 1 in 2007 (Fig.3a), which were Northwest (1.88), Southwest (1.69), Central (1.52), North (1.49) and Northeast (1.15), locating in Group III and Group IV. On the contrary, the three regions with ETT values lower than 1 were East coast (0.70), South coast (0.60) and Beijing-Tianjin (0.57), locating in Group I. The regional ETT value difference between the highest and lowest was 3.3 times in 2007. However, the regional inequality gap continued enlarging, becoming 7.9 times with highest ETT value reaching 3.16 (Northwest) and lowest ETT value at 0.40 (Beijing-Tianjin) in 2017 (Fig.3c). From the provincial perspective, similar laws can be also proved, where the ratio between the highest and the lowest provincial ETT values changed from 8.2 in 2007, to 33.6 in 2017 (Supplementary Table S11 and Fig.S5).

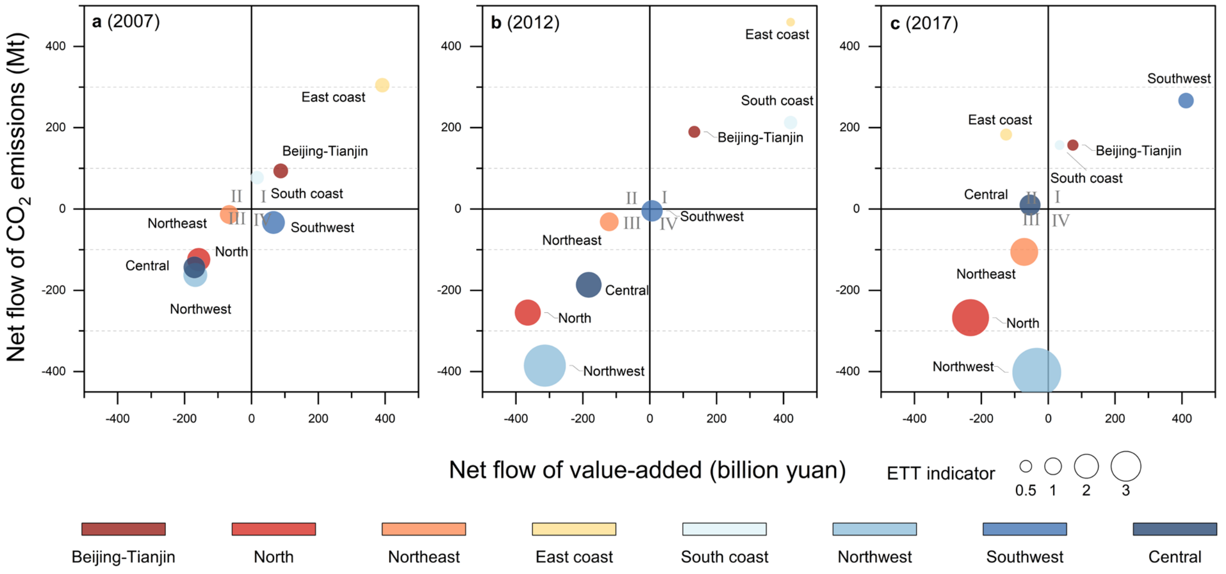

Figure 3 | Emission terms of trade (ETT) changes by regions. The horizontal axis represented net value-added (unit: billion yuan) and the vertical axis referred to net CO_2 emissions (unit: million tons). Group I, both positive net value-added and CO_2 emissions; Group II, positive net CO_2 emissions but negative net value-added; Group III, both negative net value-added and CO_2 emissions; and Group IV, positive net value-added but negative net CO_2 emissions. The size of the bubbles represents the ETT value, and bigger means higher. The colour of the bubbles corresponds to the different regions.

3.4 Changes of Carbon inequality indicated by Gini coefficient

In order to reflect China's carbon inequality overall changes during 2007-2017, the carbon-related Gini coefficient (C-Gini) was built in this study. The C-Gini of China was rising with 0.21 in 2007, 0.25 in 2012 and 0.30 in 2017 from the production-based perspective (Fig.4a-c), while the consumption-based C-Gini shows the same trend with 0.12 in 2007, 0.13 in 2012 and 0.18 in 2017 (Fig.4d-f). This proves that China's carbon inequality related to value-added was deteriorating during the last decade regardless of production or consumption perspective. A clear phenomenon can be seen from the C-Gini figure that the provinces showed a cluster character, where the red parts are aggregated at the beginning of horizontal axis, while the blue parts are accumulated at the end of the axis. This can be explained as the red parts, such as Beijing, Shanghai, Guangdong, Jiangsu mainly export high-tech products (i.e. mobile cars, mobile phones, computers, household appliances) to other provinces, which are high value-added but low carbon-intensive, while the blue parts, such as Ningxia, Inner Mongolia, Shanxi, Xinjiang mainly export primary products (i.e. coal, oil, coke, gas) within domestic trade, which are low value-added but high carbon-intensive.

From the production view, the exacerbated carbon inequality can be clearly seen from the C-Gini, which shows changes of accumulated value-added and CO_2 emissions. For example, provinces (the blue parts) with 20% (from accumulated 80%-100%) of total value-added emitted 32.9% of total CO_2 emissions in 2007, while this figure was worsened to 36.7% in 2012, and 42.6% in 2017 (Fig.4a-c). This can be also explained by the different economic development pace between the east and west. For example, the value-added of Beijing increased 25.2% (constant price, same for below) during 2007-2012 and 11.4% during 2012-2017. However, the production-based CO_2 emissions of Beijing is declining during the last decade, making the PBEI even smaller, with 1.0t/ten thousand yuan in 2007 and 0.5t/ten thousand yuan in 2017 (Supplementary Fig.S2a-c). On the contrary, the value-added of Gansu province increased about 39.8% during the last decade, while the production-based CO_2 emissions of Gansu has increased faster (68.9%), leading to higher PBEI, with 3.2t/ten thousand yuan in 2007 and 4.0t/ten thousand yuan in 2017, as stated before (Supplementary Fig.S2a-c). This enlarging phenomenon was obvious for the western provinces; while the PBEI of the eastern provinces were decreasing, making carbon inequality of China deteriorate during 2007-2017.

By contrast, China's carbon inequality is relatively weak from the consumption view, while showing the same exacerbated trend during 2007-2017. Provinces (the blue parts) with 20% of total value-added emitted 26.8% of total CO_2 emissions in 2007, while this figure was worsened to 28.1% in 2012, and 33.7% in 2017 (Fig.4d-f). It is worth noting that during the period of 2012-2017, affluent eastern provinces gained more economic benefits through industry structure change, and the consumption structure tend to be green, leading to fast economic growth with a relatively slow or negative carbon emission growth. For example, the value-added of Beijing increased 10.5% from 2012 to 2017, while the consumption-based CO_2 emission reduced 15.2%, making the CBEI of Beijing decline from 2.1 to 1.7t/ten thousand yuan. Same trend happens for other well-developed provinces, like Shanghai (from 2.5 to 1.7), Jiangsu (from 2.3 to 2.0) and Shandong (from 2.8 to 2.0) (Supplementary Fig.S2e-f). While less developed western provinces continued relying on traditional carbon-intensive industry to survive in this economic battle, leading to more consumption of carbon-intensive products to support its industry development; Besides with the improved living standard, people started to enjoy a better life with consumption of televisions, refrigerators, automobiles, leading to quick increase of consumption-based CO_2 emissions. For example, the value-added of Xinjiang province increased 2.5% during 2012-2017, while the consumption-based CO_2 emissions increased high up to 52.3%.

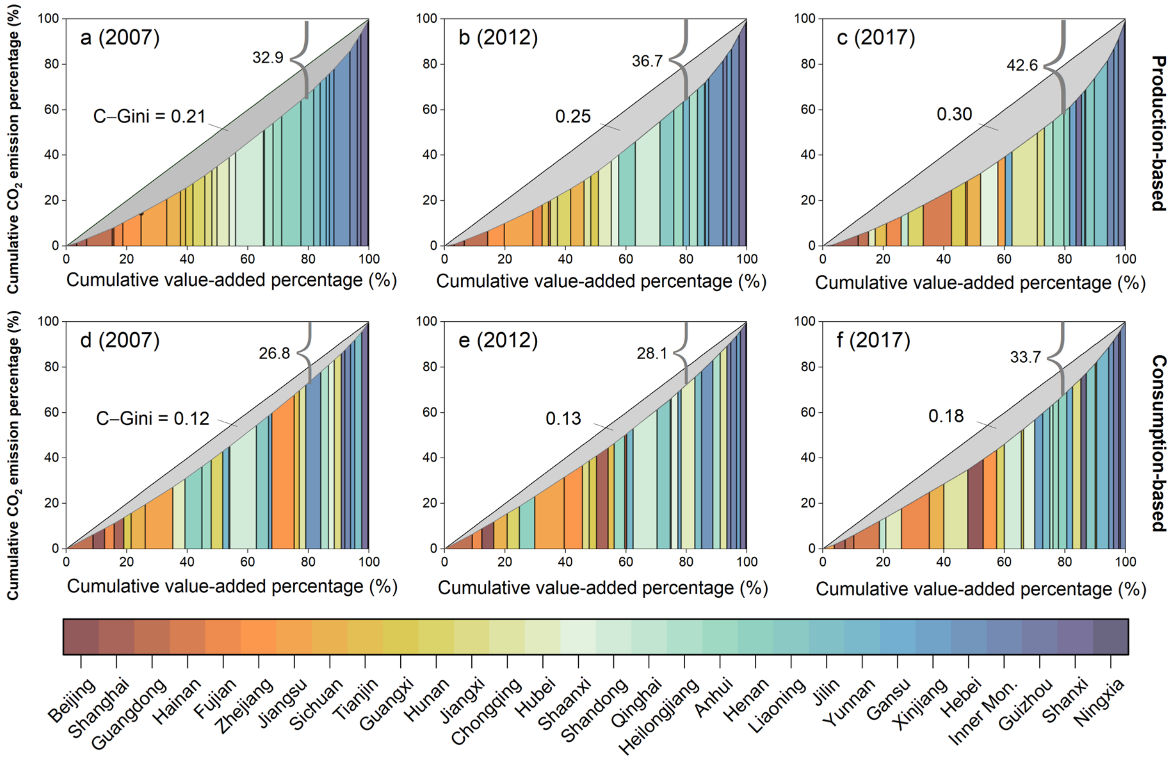

Figure 4 | Carbon-related Gini coefficient changes from 2007 to 2017. a-f are based on relationship between cumulative percentage of CO_2 emission and value-added. **a-c** are calculated from production perspective, while **d-f** are calculated from consumption perspective. The provinces with different colors are ranked by production-based emission intensity (CO_2 emissions per value-added) in 2007, where Beijing with the reddest color represents the smallest, and Ningxia with the bluest means the highest.

4. Discussion and policy implication

During the China's 12th Five Year Plan (2011-2015), China's government set different reduction targets of carbon intensity between the east and west[59], however, the eastern provinces with stricter reduction targets chose to importing even more carbon-intensive products from less developed western provinces where carbon policy was less demanding, leading to additional outsourcing and carbon leakage[7]. Researchers found that the Western Development Strategy of China did bring economic blooms to the middle and west provinces through industry transfer, but it succeeded at the expense of high CO_2 emissions embodied in trade, where the west provinces undertook the carbon leakage from the east, leading to higher territory-based CO_2 emissions[7, 13, 27].

In this study, we have not only found the similar phenomenon that more trade-related CO_2 emissions are emitted within China during 2007-2017, but also showed that China's carbon inequality became deteriorated in this trade process (ETT values and C-Gini changes), which was an undesirable result. What's worse, we have also found that the economic gains (net value-added) of west were deprived gradually by the east through trade. During the last decade, the eastern provinces imported more carbon-intensive and low-valued products from the west and exported high value-added but low carbon goods in reverse, leading to exacerbated national carbon inequality (production-based C-Gini changed from 0.21 to 0.30). In 2017, the east coast provinces (Jiangsu and Shanghai) had achieved win-win status (net value-added outflow and CO_2 emission inflow), while the Northwest provinces (Ningxia and Xinjiang) entered into lose-lose situation (net value-added inflow and CO_2 emission outflow) or emitted large amount of CO_2 emission with little net economic reward (Inner Mongolia and Shanxi). Interestingly, we have also found that due to strong consumption increase, the southwest provinces (Guangxi and Yunnan) had shifted from net carbon & value-added exporters to net carbon & value-added importers, stepping into the earlier development mode of the east (the year of 2007).

Therefore, facing the exacerbated carbon inequality and in order to realize the 18% reduction target of carbon intensity set for the China's 14th Five Year Plan, the middle and western regions should set strict admittance standards for energy-intensive plants that transferred from the eastern region and develop renewable energy. Firstly, only through high carbon reduction pressure, the west region may choose those low-carbon industries and would like to develop low carbon technology. However, undertaking the industrial transfer from the east is a challenge that the western region have to face, the western region should also pay attention to the transfer of knowledge and technology, as advocated by other scholars[60, 53, 12]. Secondly, building China's wide carbon market (only 2162 coal-power plants included up to now) containing more carbon-intensive industries (steel, cement, coal chemicals, *et al*) accompanied with proper carbon price, may be an effective means to alleviating the provincial carbon inequality. As this approach will stimulate companies' reduction motives, which means that saving CO_2 emissions equals to saving money, and provide a great chance for the west, where most heavy industries located. Thirdly, the west should take full advantage of China's carbon peak and neutrality opportunity to realize an energy revolution, get rid of the traditional dependence on fossil energy, make full use of sufficient land and natural resources, and develop new energies with high technology such as photovoltaic and wind power. By then, the west can gain economic benefits with little additional CO_2 emissions, so that the production-based CO_2 emissions can be reduced largely.

What's more, reducing carbon emissions from consumption perspective should also be paid attention to. Firstly, the consumption-based accounting system is advocated to be built and adopted as soon as possible in China[61, 62, 63]. Capacity building should be strengthened to form a well-established measurement, reporting and verification (MRV) system, so that emissions of both production- and consumption-based can be reported to the public. Secondly, in order to distinguish the carbon emission level of different products, the carbon label is preferred[9], which can been shown on the product's package. Through the publicity of green consumption, consumers may choose low-carbon products when they know the carbon emissions of products from the carbon labels. Thirdly, market tools, for example, carbon tax, can also stimulate the production and consumption of low-carbon products. But due to the elasticity of consumers' demand for goods, carbon taxes may be imposed on producers or consumers.

This study revealed the exacerbated carbon inequality through CO_2 emission and value-added flows embodied in trade within China during 2007-2017, which showed a good reminder for the rising developing countries, especially regional industry structure is characterized within a country, to avoid unbalanced or polarized development mode, and trapping into dilemma of economic development and carbon mitigation. From a global perspective, for countries that accept the carbon-intensive industry transfer from affluent developed countries, low carbon technology and knowledge transfer should be affiliated as compulsory to avoid “lose-lose” situation through global trade.

The limitation and uncertainties associated with the results mainly derive from the MRIO tables and CO_2 emission inventory. As for MRIO tables, there are some idealized assumptions, such as the intra-regional direct consumption coefficient matrix and inter regional direct consumption coefficient matrix are fixed, which means that the intra-regional production structure and inter regional trade structure are also assumed to be fixed. However, this method is the most feasible when confronted with the absence of necessary data[64]. As for CO_2 emission inventory, the uncertainty of emission accounts may come from various sources. The activity data, emission factors, lack of completeness, and measurement errors may lead to different levels of uncertainties. Our emission data are all from CEADs database. The CEADs developers applied Monte Carlo simulation to do a lot of research on the uncertainty of emission data. For example, they found the uncertainty range for energy-related emissions fell within (−15.0%, 30.3%), the activity data was (1.9%, 12.7%), while the uncertainty range from the emission factors was (-14.6%, 29.6%) in 2017. They also compared CEADs with other emission datasets[65]. Despite limitations and uncertainties, their estimates are reliable and widely used by many researchers. In addition, in this paper, some data detail processing methods are also limited. First, sector classification of MRIO tables is different between the year of 2007 and 2012, we have to merge some sectors to make them identical. Second, our trend analysis for the past decade was based on three annual snapshots (2007, 2012 and 2017), missing the information and insights from the inter-annual variations. In the future, more advanced accounting methods or instruments may further improve the accuracy of emission inventories and MRIO tables, bringing more precision to the study results.

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Acknowledgements

This work is supported by the National Natural Science Foundation of China (41871211), the National Social Science Fund of China (22BJY070) and the China Postdoctoral Science Foundation (2022M713220).

Supporting information

Additional methods relating sector and province aggregation, and detailed results of emissions and value-added transferred are shown in Tables S1-S11 and Figures S1-S5.

Author contributions

H.Z. and W.Z. contributed equally to this work. H.Z., W.Z., Y.W. and Y.S. designed the study. H.Z. and W.Z. performed the analysis and prepared the manuscript. H.Z., Y.L. and L.P. compiled 2007, 2012 and 2017 China MRIO tables and the corresponding emission inventories. All authors (H.Z., W.Z., Y.L., Y.W., Y.S., L.P., H.L., L.C.L., T.W., C.L., H.J. and D.C.) participated in the writing of the manuscript.

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