Front. Earth Sci. 2015, 9(1): 77–90
DOI 10.1007/s11707-014-0450-y

RESEARCH ARTICLE

China's provincial CO_2 emissions embodied in trade with implications for regional climate policy

Zhangqi ZHONG[1], **Rui HUANG**[1], **Qinneng TANG**[2], **Xiaonan CONG**[3], **Zheng WANG** (✉)[1,2]

1 Key Laboratory of Geographic Information Science of Ministry of Education, East China Normal University, Shanghai 200241, China
2 Institute of Policy and Management, Chinese Academy of Sciences, Beijing 100080, China
3 Institute for Urban and Environmental Studies, Chinese Academy of Social Sciences, Beijing 100028, China

Abstract CO_2 emissions embodied in trade have an important and far-reaching impact on CO_2 emissions reduction obligations. Based on a multi-regional input–output analysis, this paper calculates China's provincial CO_2 emissions embodied in trade and analyzes CO_2 emissions embodied in trade per unit of value of trade in 30 Chinese provinces. Several climate policy options that potentially reduce the impact of trade on individual provinces are discussed. One finding from this study is that provincial CO_2 emissions embodied in trade accounted for approximately 60.02% of China's CO_2 emissions in 2007. The CO_2 emissions embodied in imports and exports for 30 Chinese provinces differ widely, and remarkable differences in the CO_2 emissions embodied in trade per unit of value of trade exist. Another important finding is that if provinces take binding commitments as a part of a coalition, instead of as individual provinces, then the impacts of trade can be reduced. Notably, however, the extent of reduction in a coalition varies in different provinces.

Keywords multi-regional input–output analysis, value of trade, cooperation

1 Introduction

Global warming due to CO_2 emissions from the burning of fossil fuels has already become one of the most important environmental issues currently faced by the people of the world (Davis et al., 2010). Worldwide consensus regarding the dangers associated with greenhouse gas emissions has led to active initiatives being taken to promote energy conservation and emissions reduction in many countries (Liu et al.,2008; Wang et al., 2012). Numerous studies have shown that China is the world's largest emitter of CO_2 (Gregg et al., 2008; IEA, 2009). Facing increasing international pressure to curb its CO_2 emissions, China has committed itself to cut CO_2 emissions per unit of GDP by 40%–45% from the level of 2005 by 2020. In order to achieve this target, the Chinese government must allocate differentiated commitments for CO_2 emissions reduction to various provinces.

Although trade has played a significant role in economic development by providing a mechanism for the efficient allocation of resources during the process of economic globalization (Amin, 1999; Feenstra, 2003), the geographic separation of consumers and the pollution emitted during the production of consumable items have been caused by trade. Trade also provides a mechanism that allows consumers to shift environmental impacts, particularly CO_2 emissions associated with their consumption, to other regions (Weber et al., 2007; Peters et al., 2008a; Li et al., 2008). Then, a part of the responsibilities for CO_2 emissions reduction that belong to the consumer are transferred to the producer (Chen and Chen et al., 2010b; Guo et al., 2012; Shi et al., 2013). Recently, important climate policy implications that have emerged from using a consumption-based approach instead of a production-based approach have been well presented, and more attention has been given to the impact of CO_2 emissions embodied in trade on carbon emissions reduction obligation assignments than before (Wiedmann et al., 2007; Weber et al., 2007; Peters, 2008; Weber et al., 2008; Chen and Chen et al., 2010b; Davis et al., 2010; Fan et al., 2010; Guo et al., 2012). Although considering CO_2 emissions embodied in trade in the context of climate policy is favorable for allocating the responsibility for CO_2 emissions reduction to different regions, from the viewpoint of equity, this allocation may pose some issues, which are

Received November 26, 2013; accepted February 20, 2014

E-mail: wangzheng@casipm.ac.cn

discussed in the following section. Given these issues, this allocation raises an increasingly challenging question to us, namely, with regions' economic and trading relations becoming more and more intimate, how should provinces respond to reduce the impact of trade on assigning the task of CO_2 emissions reduction? This is the vital question that stakeholders urgently need to answer.

At present, studies concerning China's CO_2 emissions embodied in trade can be divided into three primary types. The first type focuses on the embodied CO_2 emissions in China in a year or a period (Ahmad et al., 2003; Peters et al., 2007; Wang and Watson, 2007; Pan et al., 2008; Qi et al., 2008; Peters et al., 2008a; Zhang, 2009; Chen and Chen, 2010; Chen and Chen et al., 2010a; Chen and Zhang, 2010; Lin et al., 2010; Yan et al., 2010; Wei et al., 2011; Liu and Ma, 2011; Yang and Chen, 2013; Shao and Chen et al., 2014). Remarkably, Weber et al. (2008) examined the changing trend of the CO_2 emissions emitted in the production of exports in China from 1987 to 2005. These authors determined that one-third of China's CO_2 emissions result from the production of exports, which could be a main cause for the rise in Chinese CO_2 emissions, and the total emissions embodied in China's imports are substantial.

Notably, some important studies have been investigated by Chen and his group. For example, according to the study conducted by Chen and Chen (2010), greenhouse gas emissions (GHG), in terms of CO_2, CH_4, and N_2O, released by China in 2007 of approximately 25.41%, 35.34%, and 64.33%, respectively, are embodied in final consumption, whereas the percentages for gross capital formation (gross fixed capital formation and change in inventories) are 42.28%, 34.91%, and 15.20%, respectively, and those percentages for exports are 32.31%, 29.75%, and 20.47%, respectively.

The second type focuses on the CO_2 emissions embodied in international trade with major trading countries, such as China and the USA (Shui et al., 2006; Xu et al., 2009; Guo et al., 2010), China and Japan (Liu et al.,2010; Dong et al., 2010), as well as China and the UK (Li et al.,2008). In general, these results have shown that the CO_2 emissions embodied in international trade of China's exports are higher than those of China's imports. Through international trade, significant environmental impacts have shifted from developed countries to China. Hence, China, more than other countries, is under great pressure to cut emissions. Given this trend in the international trade cycle, consumers in developed countries should be held at least somewhat responsible for CO_2 emissions occurring in other countries because of their demand for low-priced goods. However, Weber et al. (2008) and Chen and Zhang (2010) note that most of China's CO_2 emissions result from the rapidly expanding infrastructure and that the inefficient coal-powered electricity system requires urgent attention.

The third type focuses on China's provincial CO_2 emissions embodied in trade and on the inter-regional transfer of carbon emissions. Current studies of this type are relatively limited. Zhang et al. (2011) calculated China's provincial CO_2 emissions embodied in inter-provincial trade for 2002 and studied the influence of embodied CO_2 emissions on the calculation of each province's carbon emissions basis. Meng et al. (2011) examined the inter-regional transfer of CO_2 emissions embodied in power transmission. These authors found that the transfer of CO_2 emissions embodied in power transmission is gradually significant in China, from the eastern area to the central and western areas, particularly energy production provinces in the central area, which leads to the distortion of measurements of the emissions and emissions intensity. Shi et al. (2012) estimated the carbon footprint of each province and the inter-provincial transfer of carbon emissions in China. These authors found that there are significant differences in the carbon footprint and in the per capita carbon footprint among provinces and that the developed coastal provinces should bear more of the carbon emissions reduction obligation.

These studies primarily analyzed the characteristics of the inter-regional transfer of carbon emissions and the impact of CO_2 emissions embodied in inter-provincial trade on the responsibility of provinces for CO_2 emissions reduction in China. However, the important roles played by international trade in provincial CO_2 emissions have not received proper attention. In fact, for certain provinces, such as Guangdong and Zhejiang in the eastern area, international trade is of great significance for promoting economic development, which also has a significant impact on their CO_2 emissions. Moreover, the different impacts of international trade on CO_2 emissions in different provinces were mentioned by Meng et al. (2011). In response to the above mentioned problems, Guo et al. (2012) analyzed the characteristics of China's provincial CO_2 emissions embodied in international and inter-provincial trade and estimated each province's CO_2 emissions under two approaches (a consumption-based approach and a production-based approach). These authors noted that the provincial contribution to China's CO_2 emissions can be reflected based on a consumption-based approach and that the eastern area plays an important role in China's CO_2 emissions reduction. Additionally, these authors indicated that the central and western areas require supportive policies concerning CO_2 emissions reduction to avoid the transfer of industries with high emissions. Furthermore, using Beijing as an example, Zhou and Chen et al. (2010) and Chen and Guo et al. (2013) calculated the carbon emissions embodied in the commodity flows of both international and domestic imports at the urban scale based on the input–output analyses in 2002 and 2007, respectively.

Although previous studies have provided an important theoretical basis and reference scheme for policy-makers to use in allocating responsibility for CO_2 emissions reduction to each province from the perspective of equity and reason, by calculating provincial CO_2 emissions embodied in international and inter-provincial trade, as well as by analyzing the inter-provincial transfer of carbon emissions in China, these analyses may lead to two main issues. First, it is possible to provide justification for related regions to discuss trade protectionism in climate policy, and its consequence is usually that border-tax adjustments are used by related regions to reduce the impacts of trade (Cendra, 2006; Fan et al., 2010), which will likely bring about trade barriers and even the risk of trade frictions. Second, there are large economic costs associated with the participation in a regional climate regime (Peters et al., 2008b). For those provinces with a large share of exports in carbon-intensive production, production may be shifted to nonparticipating provinces to avoid their responsibility for CO_2 emissions reduction (Peters et al., 2007). In addition, it is most likely difficult to promote the achievement of China's total CO_2 emissions reduction target. Moreover, the possible negative impact of the transfer of production on the development of the local economy is the most important issue. Those provinces with a large share of imports in carbon-intensive consumption will face increasingly severe pressure to reduce emissions, which, in turn, may hamper economic development. Therefore, methods to reduce the impact of trade on individual provinces in climate policy appear to be particularly critical.

Regrettably, however, there is little research concerning this issue. In fact, research regarding methods that can be used to reduce the impact of trade on individual countries within the context of the Kyoto Policy has already aroused scholars' attention. Victor et al. (2005) studied how individual countries should conduct cooperation in climate policy. Peters et al. (2008a) determined that CO_2 emissions embodied in trade are generally lower for a coalition compared with individual members of the coalition, and that this situation may reduce competitiveness concerns and encourage participation. In addition, Chen & Chen (2011b) also supposed that the mutual understanding and cooperation of coalitions would be helpful for drawing an acceptable agreement to confront climate change. According to the above research results, considering the impact of CO_2 emissions embodied in international trade on the responsibility for emissions within the context of climate policy, a more effective method for individual countries with binding commitments to reduce the impact of trade may be to encourage coalition formation in order to stimulate cooperation for global carbon mitigation. Then, for a vast country such as China, there is a significant difference in regional economic development among provinces. Likewise, the CO_2 emissions of each province are remarkably different in China, and these differences are affected by trade (Guo et al., 2012). Considering the impact of the embodied CO_2 emissions on the carbon emissions reduction obligation in the context of climate policy, can groupings of provinces form coalitions to reduce the impact of trade in China? Furthermore, which provinces should be grouped together to form a coalition to conduct regional cooperation, and is the participation of a province in a coalition more conducive to reducing the impact of trade compared with individual provinces? This article can naturally answer the former question after solving the latter question.

The remainder of this paper is organized as follows. The following section focuses on methodology and data. The calculation results and implications for regional climate policy are discussed in Section 3. A description of the conclusions is provided in Section 4.

2 Methodology and data

2.1 Model

Input–output (IO) analysis can capture indirect environmental impacts caused by upstream production and is suitable for the estimation of pollution and resource use embodiments of traded commodities. This technique has been recognized as important for quantifying the embodied GHG and resources used in one region for the production of goods and services exported to another region (Machado et al., 2001; Wiedmann et al., 2007; Liang and Fan et al., 2007; Park et al., 2007; Peters, 2008; Wiedmann, 2009; Chen and Chen, 2010; Chen and Chen et al., 2010a, 2010b; Chen and Zhang, 2010; Davis et al., 2010; Zhou and Chen et al., 2010; Chen et al., 2011; Chen and Chen, 2011a, 2011b; Guo et al., 2012; Shi et al., 2012; Chen and Guo et al., 2013; Chen and Chen, 2013; Li and Alsaed et al., 2014; Shao and Chen et al., 2014). In the literature, single-region input–output (SRIO) analysis and multi-region input–output (MRIO) analysis are commonly used to estimate the CO_2 emissions embodied in trade within an IO analysis framework (Wiedmann et al., 2007; Peters, 2008). The results have shown that MRIO analysis is superior to SRIO analysis for analyzing the inter-regional trade effects between regions and for reflecting the relations between different sectors (Davis et al., 2010; Guo et al., 2012).

The objective of this paper is to estimate provincial CO_2 emissions embodied in trade and to discuss CO_2 emissions embodied in trade, with implications for regional climate policy in China. Thus, MRIO analysis has been adopted for the purposes of this study. Additionally, Peters (2008) found that when using IO analysis there are two main approaches for determining the embodied CO_2 emissions of imported goods and services. One approach considers bilateral trade between regions and the other approach considers trade to final consumption and endogenously determines trade to intermediate consumption. The results presented in this paper also indicate that the former approach determines the emissions in one region to produce the bilateral trade with another region and does not split the bilateral trade flow into components to intermediate and final consumption. Because it is unnecessary to assess the imports required to produce bilateral trade, this approach is considered the simplest and the most transparent (Peters et al., 2008a). In this study, the former approach was used to quantify the CO_2 emissions embodied in trade (EET) in climate policy.

According to the study conducted by Peters (2008), as well as considering the impacts of international and inter-provincial trade on the embodied CO_2 emissions of each province in China, the total CO_2 emissions occurring in each province explicitly decomposed into components for provincial and traded components can be expressed as follows:

$$E_r = F_r(I - A_r)^{-1}\left(Y_r + \sum_s e_{rs} + \sum_t f_{rt}\right), \tag{1}$$

where F_r is a row vector, with each element representing the CO_2 emissions per unit industry output; I is the identity matrix; A_r are the inter-industry requirements of produced products of province r demanded by provincial industries in province r; Y_r are the products produced and consumed in province r; e_{rs} are the bilateral exports in inter-provincial trade from province r to province s; and f_{rt} are the bilateral exports in international trade from province r to country/region t. Notably, however, when CO_2 emissions embodied in international trade are calculated, the “domestic technology assumption” is used, which assumes that the emissions factors of imported goods are identical to those factors used domestically in a given sector (Weber et al., 2008). Although some overestimation of CO_2 emissions embodied in import are caused, Guo et al. (2012) determined that the results can be regarded as approximate. Thus, the key assumption employed in IO analysis is also used in this study. This assumption allows Eq. (1) to be decomposed into the following components for the demand of province r on provincial production in province r:

$$E_{rr} = F_r(1 - A_r)^{-1}Y_r. \tag{2}$$

The CO_2 emissions embodied in inter-provincial trade from province r to province s are expressed as follows:

$$E_{rs} = F_r(1 - A_r)^{-1}e_{rs}. \tag{3}$$

The CO_2 emissions embodied in international trade from country/region t to province r are expressed as follows:

$$M_{tr} = F_r(1 - A_r)^{-1}f_{tr}. \tag{4}$$

The emissions embodied in exports (EEE) from province r to all other regions are expressed as follows:

$$E_r^e = \sum_s E_{rs} + \sum_t M_{rt}. \tag{5}$$

The emissions embodied in imports (EEI) are obtained by reversing the summation as follows:

$$E_r^m = \sum_s E_{sr} + \sum_t M_{tr}. \tag{6}$$

Then, for province r, the emissions embodied in trade (EET) can be expressed as follows:

$$E_r^{EET} = E_r^e + E_r^m. \tag{7}$$

Another quantity that is often discussed in the literature is the balance of the CO_2 emissions embodied in trade (BEET) of province r, which can be expressed as follows:

$$E_r^{BEET} = E_r^e - E_r^m. \tag{8}$$

Different CO_2 emissions accounting approaches (particularly for a consumption-based approach and a production-based approach) in climate policy have a significant impact on allocating the responsibility for anthropogenic emissions to regions (Munksgaard et al., 2001; Peters et al., 2008a; Guo et al., 2012). Thoroughly exploring the impact of emissions accounting approaches on provincial commitments for CO_2 emissions reduction in China, we define the production-based emissions inventory as the total emissions occurring from economic production within a province as follows:

$$E_r^{prod} = E_r. \tag{9}$$

We define the consumption-based emissions inventory as the total emissions occurring from economic consumption within a province as follows:

$$E_r^{cons} = E_r^{prod} - E_r^e + E_r^m = E_r - E_r^{BEET}. \tag{10}$$

Moreover, to analyze the CO_2 EET per unit of value of trade among provinces in China, the calculated method adopted in this paper can be expressed as follows:

$$\rho_r = \frac{E_r^e / Q_r}{E_r^m / P_r}, \tag{11}$$

where Q_r is the value of trade in the export of province r and P_r is the value of trade in the import of province r. ρ is a ratio and, by definition, is dimensionless. For example, if ($\rho = 1$), then the EEE per unit of value of the trade of a province’s exports is equal to the EEI per unit of value of trade of a province’s imports. If $\rho > 1$, then the higher its value is, the higher the EEE per unit of value of trade of a province’s exports is.

2.2 Data

This paper adopts the Chinese MRIO tables of 2007, which are the most recent and complete data concerning China’s 30 provinces and municipalities of all of the published MRIO tables (Hong Kong, Macao, Taiwan, and Tibet are not included because of a lack of data). The table, covering 30 sectors, is from the study conducted by Liu et al. (2012), which has gradually been used by researchers (Li et al., 2013). In addition, the table not only provides data concerning China's imports and exports but also concerning China's 30-region trade for 30 sectors in inter-provincial trade. Each sector's CO_2 emissions per unit of output are required to calculate embodied CO_2 emissions coefficients. There are no direct statistics data; thus, the calculated method can be described as follows: First, based on the quantity of energy consumption data from the energy balance table of each province in 2007 (CESY, 2008) and on the CO_2 emissions factors of various types of energy from the Intergovernmental Panel on Climate Change (IPCC) reference approach (IPCC, 2006), we calculated the CO_2 emissions per unit of output of each sector in each province for the year 2007. In addition, other data regarding each province, such as the population, gross domestic product (GDP), area, and industrial structure, were obtained from the 'China Statistical Yearbook 2008' (National Bureau of Statistics of China, 2009).

Finally, it is important to note that there are 30 sectors in the MRIO tables, but only 6 sectors in the energy balance tables. At present, two data treatment schemes can be used to make these tables compatible. One treatment scheme is to aggregate the IO data to the level that matches the energy consumption data. The other treatment scheme is to disaggregate the energy consumption data to the level that matches the IO data (Su et al., 2010). Opinions regarding the determination of which schemes to adopt are divided among researchers. For instance, Machado (2000) suggests using the former, whereas Lenzen et al. (2004) advocate the latter. Additionally, Su et al. (2010) suggested that both schemes have strengths and weaknesses. The former guarantees data accuracy without incurring potential errors from imposing extra assumptions, whereas the latter retains all IO data information, which is matched with an energy dataset enlarged by making certain reasonable assumptions. To retain as much MRIO table information as possible, the latter scheme was adopted for this study.

3 Results and discussion

3.1 Emissions embodied in trade

Based on the above model and data, the calculated result shows that provincial CO_2 emissions embodied in trade are 3082.95 million tons[1], which account for approximately 60.02% of China's CO_2 emissions in 2007. Apparently, this percentage is large, which explicitly indicates that provincial CO_2 EET has important implications for regional climate policy in China.

As shown in Table 1, the CO_2 EEI and EEE values differ widely for the 30 Chinese provinces and municipalities. From the perspective of the EEI, this value can vary considerably for individual provinces. Approximately half of the provinces have more than 30% EEI, and the range of values is between 7.66% (Shanxi) and 71.59% (Zhejiang), which indicates that there are considerable regional differences among provinces in China. Moreover, the top seven with the highest EEI for the 30 Chinese provinces and cities studied are Zhejiang, Tianjin, Jilin, Guangdong, Shanghai, Jiangxi, and Beijing. Additionally, further calculation suggests that the ratio between the EEI of these seven provinces and cities and the total EEI in China is 43.12%. Notably, however, here are four provinces and cities (Zhejiang, Tianjin, Jilin, and Guangdong) with approximately 50% EEI, which suggests that those provinces have a larger share of imports in carbon-intensive consumption. Thus, the impact of trade on the CO_2 emissions reduction commitments undertaken by these provinces may be greater than others. For some provinces in western China, including Sichuan, Gansu, Ningxia, Xinjiang, Inner Mongolia, Guizhou, and Shanxi, the EEI values are relatively low compared with other regions, accounting for approximately 8.71% of the total EEI in China.

From the perspective of the EEE, the EEE ranges from 11.95% (Jiangxi) to 47.19% (Gansu) for individual provinces. Fourteen of the 30 provinces and cities have an EEE of more than 30%, which indicates that regional differences are also clear. Of the 30 Chinese provinces and cities studied, the seven with top ranking EEE values are Gansu, Inner Mongolia, Yunnan, Xinjiang, Tianjin, Shaanxi, and Hebei. Similarly, the ratio between the EEE values of these seven provinces and cities and the total EEE in China is 31.96%. Also of concern are the two provinces, Gansu and Inner Mongolia, with EEE values of 44.97% and 43.10%, respectively, which suggest that these EEE values account for approximately half of the concerned provinces' CO_2 emissions in 2007. For some provinces and cities, such as Jiangxi, Chongqing, Fujian, Shandong, Sichuan, Jiangsu, and Zhejiang, EEE values are lower than other provinces, accounting for approximately 15.81% of the total EEE in China.

Table 1 also displays the BEET among provinces in China. Twelve of 30 provinces and cities total the net input of embodied CO_2 emissions in trade for the year 2007. Most provinces and cities of eastern China, such as Zhejiang, Jilin, Tianjin, Beijing, Guangdong, and Shanghai, have the highest net input of embodied CO_2 emissions. Apparently, CO_2 emissions through consuming goods and services that are produced in other regions are avoided by these provinces. In addition, the seven provinces with the highest net output of embodied CO_2 emissions are primarily centered in central and western China, including Inner Mongolia, Gansu, Xinjiang, Shanxi, Guizhou, Yunnan, and Ningxia, which indicates that many goods in carbon-intensive production are moved from these provinces to other regions. As for the BEET, according to the

---

[1] According to another study conducted by Guo et al. (2012), China's provincial CO_2 emissions embodied in trade are 2869.63 million tons in 2002.

study conducted by Peters et al. (2008a), this tendency indicates that it is better to export environmental impacts, particularly for CO_2 emissions, than to import (positive BEET).

From a climate change perspective, Peters et al. (2008a) found that it is more desirable to have production occur where production is environmentally preferable and then to trade the products locally and internationally. Therefore, some provinces may have a positive or negative BEET, depending on their comparative environmental advantage from that perspective. However, beyond that perspective, some provinces and municipalities, such as Beijing and Tianjin, have notably more EEI, which indicates that if the impacts of trade are considered in regional climate policy, then these provinces should bear a greater carbon emissions reduction obligation. Additionally, further economic development of these regions may also be more vulnerable to certain effects. Furthermore, as shown in the second and third columns listed in Table 1, the higher the EEE values are, the more obvious provincial CO_2 emissions affected by a production-based approach are. Specifically, the CO_2 emissions volume of some provinces, such as Inner Mongolia and Gansu, will be exaggerated under a production-based accounting principle, which may cause more CO_2 emissions reduction commitments to be undertaken. A high share of EEE not only affects

Table 1 China's provincial emissions embodied in trade for the year 2007

	Production ($MtCO_2$)	Consumption ($MtCO_2$)	EEE (%)	EEI (%)	BEET (%)	E^e/Q ($tCO_2/10^4$yuan)	E^m/P ($tCO_2/10^4$yuan)	ρ
Anhui	105.57	114.84	28.91	37.68	−8.78	0.54	0.66	0.81
Beijing	116.80	142.79	24.11	46.36	−22.26	0.30	0.52	0.58
Fujian	105.84	116.08	15.49	25.17	−9.68	0.24	0.45	0.52
Gansu	117.19	81.19	47.19	16.47	30.72	3.06	0.98	3.12
Guangdong	398.14	483.44	28.68	50.10	−21.42	0.28	0.58	0.48
Guangxi	81.80	78.74	26.86	23.12	3.74	0.63	0.52	1.21
Guizhou	158.32	120.31	33.80	9.79	24.01	2.92	0.63	4.61
Hainan	19.85	19.48	36.30	34.46	1.84	1.24	0.87	1.43
Hebei	394.72	374.53	37.08	31.97	5.12	1.01	1.12	0.91
Henan	201.47	200.75	30.50	30.13	0.36	0.69	0.72	0.96
Heilongjiang	152.52	138.59	30.68	21.54	9.14	1.02	0.75	1.37
Hubei	124.02	121.96	22.17	20.51	1.66	0.96	0.84	1.14
Hunan	144.53	142.36	23.09	21.59	1.50	0.79	0.78	1.01
Jilin	115.26	152.07	30.96	62.89	−31.93	0.77	1.28	0.60
Jiangsu	370.57	436.11	19.08	36.76	−17.68	0.27	0.69	0.39
Jiangxi	81.10	109.22	11.95	46.62	−34.67	0.44	1.36	0.32
Liaoning	342.91	298.28	34.47	21.45	13.02	1.32	1.09	1.21
Inner Mongolia	198.91	127.20	47.03	10.97	36.05	2.04	0.71	2.85
Ningxia	75.33	65.05	26.15	12.50	13.65	3.25	1.01	3.23
Qinghai	53.65	51.00	23.61	18.69	4.93	3.23	1.62	2.00
Shandong	303.13	348.71	15.72	30.76	−15.04	0.35	0.92	0.38
Shanxi	373.26	277.55	33.30	7.66	25.64	3.71	0.93	3.97
Shaanxi	127.24	113.58	37.34	26.61	10.73	0.88	0.66	1.34
Shanghai	163.02	197.53	28.37	49.54	−21.17	0.24	0.43	0.56
Sichuan	154.36	153.71	17.18	16.76	0.42	0.75	0.64	1.16
Tianjin	84.98	107.10	38.21	64.23	−26.02	0.40	0.72	0.56
Xinjiang	144.58	101.53	42.05	12.27	29.78	2.29	0.57	4.01
Yunnan	91.42	72.62	46.20	25.64	20.56	1.49	0.51	2.91
Zhejiang	258.20	387.41	21.55	71.59	−50.04	0.30	1.12	0.26
Chongqing	78.23	93.68	12.72	32.47	−19.75	0.35	0.74	0.47

Note: For each province, we show the production-based emissions, E_r^{prod}; the consumption-based emissions, E_r^{cons}; the percentage EEE, $\frac{E_r^e}{E_r^{prod}}$; the percentage EEI, $\frac{E_r^m}{E_r^{prod}}$; and the percentage BEET, $\frac{E_r^{BEET}}{E_r^{prod}}$.

competitiveness but also participation in binding emission reductions because deep emissions cuts will ultimately affect export industries and even economic development (Peters et al., 2008a). Therefore, those provinces will have identical position and interest within the context of climate policy i.e., those provinces are more likely to perform regional cooperation for carbon mitigation. However, for other provinces and cities with a net input of embodied CO_2 emissions, such as Zhejiang, Beijing, and Shanghai, where trade provides a mechanism to efficiently allocate resources in the process of economic development, environmental impacts have also been shifted. Then, some of the CO_2 emissions reduction responsibilities that belonged to these provinces are transferred. Consequently, this transfer also provides an important basis for these provinces to form coalitions concerning emissions reduction.

Based on the above studies, we can see that there is some relation between various province characteristics, such as the GDP and population, as well as the industrial structure and EET. Take Beijing, Shanghai, Zhejiang, and Guangdong, for example. These provinces and cities have the highest EET values and also have the largest GDP and developed modern service industries. In addition, other provinces with a greater EET value, such as Shanxi and Inner Mongolia, are characterized by high-energy consumption and high emissions, which primarily belong to secondary industry. Next, given the possible relations and the possible importance of EET in shaping the provinces' environmental profiles, we performed regressions. The results are shown in Tables 2–4.

Generally speaking, GDP is found to be associated with a significantly positive coefficient, suggesting that the provinces with larger GDP have higher EET. This result is most likely because as the regional economy grows, the volume of bilateral trade between regions is likely to continue rising. However, as for the impact of secondary industry, the estimated coefficients are positive but not significant. We can infer that the greater the proportion of secondary industry, the higher EET provinces may have. One possible reason is that energy intensive industries primarily hold a large proportion of secondary industry, which is the main contributor to the transfer of embodied CO_2 emissions in bilateral trade between regions. Most notably, a negative coefficient is conversely estimated for primary and tertiary industries. Although the coefficient is not statistically significant, the negative sign still indicates that the larger the weight ratio of primary industry and tertiary industry is the lower EET provinces may have. One alternative reason is that the two industries may have a smaller demand for carbon-intensive consumption, possibly implying that if provinces develop primary industry or tertiary industry to increase the proportion in the national economy, then the provinces may negate some of the negative consequences of trade.

To conclude, GDP, area, and secondary industry exhibit a positive impact on provincial EET, and the only the variable that is statistically significant is GDP. The

Table 2 The regression coefficients of China's provincial EET, GDP, population, area, and primary industry

		Tolerance	Variance Inflation Factor (VIF)
Constant	0.172(1.870)*		
GDP	0.738(2.807)**	0.206	4.866
Population	–0.014(–0.070)	0.239	4.188
Area	0.140(0.940)	0.899	1.112
Primary industry	–0.240(–1.224)	0.482	2.074
R^2	0.649***		
F	11.551***		

Note: According to the research requirements, all raw data have been standardized before regressions were performed, and the figures in parentheses are standard deviations (the same procedure was performed below, in Table 3 and Table 4). *, **, and *** represent significance at the 10%, 5%, and 1% statistical levels, respectively.

Table 3 The regression coefficients of China's provincial EET, GDP, population, area, and secondary industry

		Tolerance	VIF
Constant	–0.036(–0.384)		
GDP	0.892(4.749)***	0.382	2.621
Population	–0.182(–1.197)	0.407	2.457
Area	0.058(0.049)	0.908	1.100
Secondary industry	0.237(1.713)	0.870	1.150
R^2	0.667***		
F	12.516***		

Note: *, **,and *** represent significance at the 10%, 5%, and 1% statistical levels, respectively.

Table 4 The regression coefficients of China’s provincial EET, GDP, population, area, and tertiary industry

		Tolerance	VIF
Constant	$0.163(1.706)^{*}$		
GDP	$1.049(5.054)^{***}$	0.335	2.983
Population	$-0.278(-1.489)$	0.291	3.442
Area	0.048(0.305)	0.830	1.205
Tertiary industry	$-0.214(-1.030)$	0.659	1.518
R^2	0.643^{***}		
F	11.256^{***}		

Note: *, **,and *** represent significance at the 10%, 5%, and 1% statistical levels, respectively.

estimated coefficients for the population, primary industry, and tertiary industry are negative but not significant. Nevertheless, Peters et al. (2008a) also noted that generally large regions, as classified by their GDP, population, and area, have smaller EET values, which could be interpreted as large regions being more self-sufficient. Thus, these authors suggested that regions may act in coalitions to increase their effective size to reduce the impacts of trade. However, for the 30 Chinese provinces and municipalities studied, the above result of this research shows that size may not be used as a basis for forming coalitions. Next, in order to explore how to form coalitions that perform regional cooperation for reducing carbon emissions among provinces in China, we present a deep analysis of the EET per unit of value of trade.

3.2 EET per unit of value of trade

As shown in the ninth column listed in Table 1, the value (ρ) calculated by Eq. (11) is greater than 1 for some provinces, such as Guizhou, Xinjiang, Shanxi, Ningxia, and so on, which suggests that the EEI per unit of value of trade of a province’s imports is higher than the EEE per unit of value of trade of a province’s exports. Likewise, for other provinces and cities, such as Zhejiang, Tianjin, Shanghai, Beijing, and so on, the value (ρ) is less than 1, which suggests that the EEE per unit of value of trade of a province’s exports is relatively low compared with the EEI per unit of value of trade of a province’s imports.

In addition, further analysis revealed that provinces with the value (ρ) above 1 can be divided into two types. The first type includes provinces, such as Guizhou, Xinjiang, Shanxi, Ningxia, Gansu, Yunnan, Inner Mongolia, and Qinghai. Their EET per unit of value of trade is extremely high (greater than 2), and the seventh and eighth columns listed in Table 1 show that the EEE per unit of value of trade of a province’s exports is extremely high but that the EEI per unit of value of trade of a province’s imports remains relatively low. In addition, the eight provinces with greater EEE values are the net output of embodied CO_2 emissions, and the positive BEET is extremely large. An alternative explanation could be that these provinces are the major energy-rich regions with a larger share of exports of energy intensive products with high emissions and that most of the imports from other regions are deep-processing products and high technological products with low emissions. Obviously, as these provinces provide strong support for other regions’ economic growth through trade, they also suffer most from environmental impacts shifted by other regions under the production-based accounting principle.

The second type includes provinces, such as Hainan, Heilongjiang, Liaoning, Guangxi, Sichuan, Hubei, and Hunan. Their EET per unit of value of trade is high, with a range between 1 and 2. The EEI per unit of value of trade of this type of province’s imports is also high. Moreover, these seven provinces are the net output of embodied CO_2 emissions. However, the positive BEET is approximately below 10%, which is smaller compared to some provinces in the first type. This result can most likely be explained by the requirements of these provinces for energy intensive products from other regions, but because these provinces are not the areas that are rich in energy resources, most of the exports to other regions from these provinces might not be high-carbon products. Consequently, for these provinces, trade has not only brought about some benefits but also has some inevitable environmental impacts.

Provinces showing a value (ρ) below 1 can also be divided into two types. The first type includes some provinces and cities with a highly developed economy, such as Beijing, Tianjin, Shanghai, Jiangsu, Zhejiang, and Guangdong. Table 1 indicates that the EEE per unit of value of trade of these provinces’ exports is low and that the EEI per unit of value of trade of these provinces’ imports is extremely high. Moreover, the provinces with more EEI are the net input of embodied CO_2 emissions, and the negative BEET is extremely large, i.e., the BEET is less than approximately-20%. An alternative explanation could be that these provinces are in great need of carbon-intensive products, such as cement and power from other regions, for the process of rapid socio-economic development. Additionally, the main exports of these provinces are new and high technological products with low emissions. Clearly, when trade causes a geographic separation of consumers and the greenhouse gas emitted during the production of consumable items, consumers and producers will face increasing pressure to curb CO$_2$ emissions and to share more CO$_2$ emissions reduction responsibilities under the consumption-based accounting principle. The second type in this category includes provinces and cities such as Jilin, Anhui, Fujian, Jiangxi, Shandong, and Chongqing. The EEI per unit of value of trade of these provinces' imports is high, and they are the net input of embodied CO$_2$ emissions. A possible explanation could be that these provinces remain relatively underdeveloped in terms of economic development compared with cities such as Beijing, Tianjin, and Shanghai. With a rapidly developing economy, these cities must import more products to meet local demands in bilateral trade. Therefore, a part of emissions reduction responsibilities is transferred to other regions by trade under the production-based accounting principle. Notably, although Henan and Hebei had the value (ρ) below 1 of 0.91 and 0.96, respectively, these provinces are the net output of embodied CO$_2$ emissions, and the positive BEET is relatively small (Henan, 0.36%; Hebei, 1.66%). Peters et al. (2008a) found that it is more likely for related regions with similar environmental profiles to form a coalition. Because the two provinces share some important features in common with provinces such as Hainan, Heilongjiang, and Shaanxi, and so on, their interests are identical, and it may be more advantageous to reduce the impacts of trade for these provinces by forming a coalition to conduct regional cooperation in climate policy. In summary, based on these studies, the 30 Chinese provinces and municipalities studied are divided into four groups in this paper. The first group includes Beijing, Tianjin, Shanghai, Jiangsu, Zhejiang, and Guangdong. The second group consists of Jilin, Anhui, Fujian, Jiangxi, Shandong, and Chongqing. The third group contains Guizhou, Xinjiang, Shanxi, Ningxia, Gansu, Yunnan, Inner Mongolia, and Qinghai. The fourth group includes Hainan, Heilongjiang, Shaanxi, Liaoning, Guangxi, Sichuan, Hubei, Hunan, Henan, and Hebei. The key features of these four groups are shown in Table 5.

3.3 The impact of coalition formation

Considering binding commitments, as well as the impact of trade in climate policy on assigning the task of CO$_2$ emissions reduction, is the participation of a province in a coalition more conducive to reducing the impacts of trade compared with effort made by individual provinces? Next, this article will continue the thorough analysis of the impact of coalition formation on provinces from the above study.

Figure 1 shows that provinces are more affected by trade individually than as a part of a coalition. For example, before acting in the coalition, the percentages of EEE and EEI compared with total production-based emissions for Guangdong are 28.68% and 50.10%, respectively. However, when Guangdong participates in the coalition, the percentages of EEE and EEI compared with total production-based emissions for the coalition decline greatly, reduced by 9.92% and 5.28%, respectively. The EET values are reduced if Guangdong participates in the coalition because only the EET originating outside the coalition is considered. In addition, the largest decline in

Table 5 The key features of the four groups

	$E_r^{BEET} > 0$		$E_r^{BEET} < 0$		$\rho > 1$		$\rho < 1$
	$E_r^{BEET} > 10\%$	$E_r^{BEET} < 10\%$	$E_r^{BEET} < -20\%$	$E_r^{BEET} > -20\%$	$\rho > 2$	$\rho < 2$	
The first group			√				√
The second group				√			√
The third group	√				√		
The fourth group		√				√	

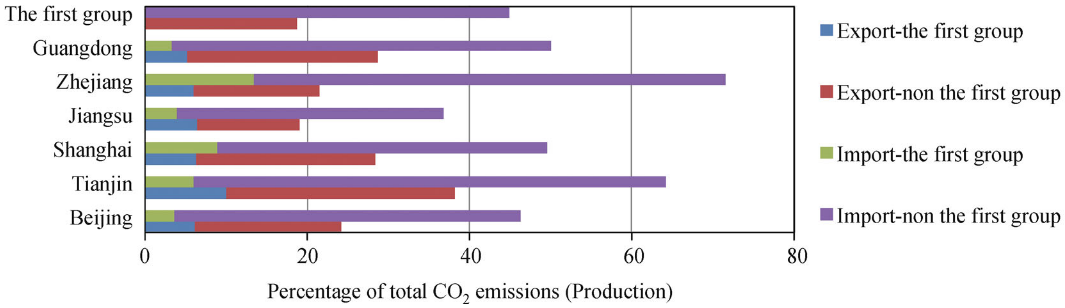

Fig. 1 EEE and EEI of the first group members, indicating the EET originating inside the coalition (left bar) and outside the coalition (right bar)

the percentages of EEE and EEI compared with total production-based emissions is seen for Tianjin, falling 19.44% to 18.76% and 19.41% to 44.82%, which indicates that this province will benefit most in the coalition. Because the smallest decline in the EET is for Beijing, falling by 5.34% (the EEE) and 1.54% (the EEI), this province will benefit least. The EET is generally lower for a coalition compared with individual members of the coalition. Peters et al. (2008a) suggested that this situation may reduce competitiveness concerns and encourage participation. The results show that if provinces participate in a coalition, instead of as individual provinces, then the impacts of trade can be reduced to some extent. However, notably, the extent of the reduction in the coalition may vary in different provinces, which is particularly apparent for Jiangsu. After acting in the coalition, the percentage of EEE compared with total production-based emissions for Jiangsu falls by nearly 0.3%. However, the percentage of EEI increases by approximately 8%, which may lead to an increase in the EET, and then more pressure will be faced by this province than before. In this case, we suggest that the stakeholder must ensure that those provinces who suffer most or benefit least obtain help, such as capital and technology from those provinces who benefit most. To conclude, for provinces and cities like Guangdong, Zhejiang, Beijing, and so on, forming a coalition is more conducive to the reduction of the impacts of trade than operating as individual provinces.

Figure 2 shows that the declines in the percentages of EEE and EEI compared with total production-based emissions for the second group members are different when these members form a coalition to conduct regional cooperation in climate policy. Importantly, the percentages of EEE and EEI for Chongqing, Shandong, and Fujian do not reduce but rise in the coalition. Specifically, the biggest declines in the EET occur in Jilin, falling by 13.56% (EEE) and 27.06% (EEI), respectively, followed by Anhui. For Fujian, if this province participates in a coalition, instead of as an individual province, then the impacts of trade cannot be reduced but rise, which highlights the rise in the percentages of EEE and EEI compared with total production-based emissions, increasing by approximately 2% and 11%, respectively. Therefore, for some members in this coalition, such as Chongqing, Shandong, and Fujian, the impacts of trade may not be reduced. However, it is beneficial for policy-makers to stimulate the emerging trend of regional cooperation for carbon mitigation.

As shown in Fig. 3, for some provinces, such as Xinjiang, Gansu, Yunnan, Guizhou, and Inner Mongolia, the EET is generally lower than before. For instance, if Yunnan participates in the coalition, then the drops in the percentages of EEE and EEI compared with total

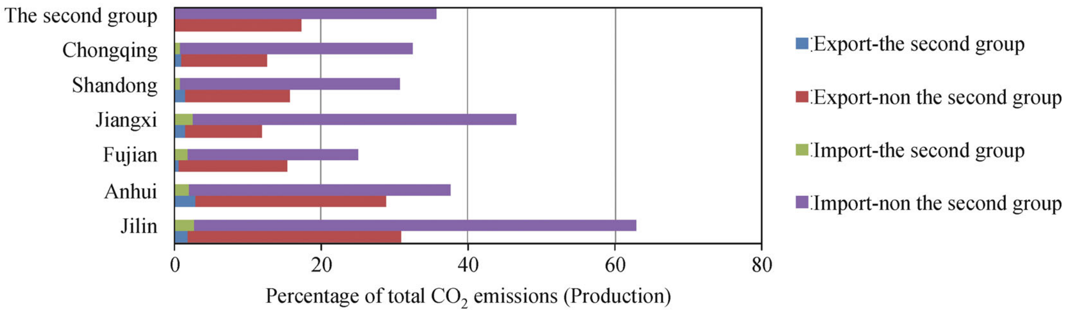

Fig. 2 EEE and EEI of the second group members, indicating the EET originating inside the coalition (left bar) and outside the coalition (right bar)

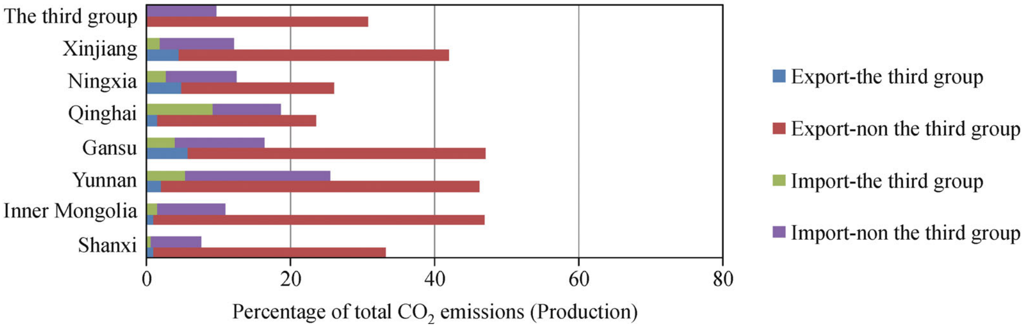

Fig. 3 EEE and EEI of the third group members, indicating the EET originating inside the coalition (left bar) and outside the coalition (right bar)

production-based emissions is evident, falling 15% to 30.85% and 16% to 9.77%. However, for Qinghai, Ningxia, and Shanxi, after acting in the coalition, the percentage of EEE to total production-based emissions for these provinces is increased to some extent. Clearly, however, the percentage of EEI is also reduced.

According to Fig. 4, if provinces act in a coalition, the EET for some provinces, such as Hebei, Liaoning, Heilongjiang, Henan, Guangxi, Hainan, Shaanxi, and Hunan, are reduced to some extent. For example, if Hebei participates as an individual, then the percentages of EEE and EEI compared with total production-based emissions are 37.08% and 31.97%, respectively. However, if Hebei participates in a coalition, then the percentages of EEE and EEI for the coalition decline greatly, falling 14.62% to 22.46% and 13.33% to 18.64%, respectively, indicating that the impacts of trade are substantially reduced. However, for the Sichuan Province, as a member that belongs to the coalition, the impact of trade cannot be reduced. An obvious representation is that the percentages of EEE and EEI compared with total production-based emissions both increase by approximately 5% and 8%, respectively. Therefore, it is necessary that those provinces that benefit most provide financial and technological aid to those provinces that suffer most or benefit least in climate policy.

In summary, the EET of individual provinces is generally larger and more variable compared with the coalition as a whole. As shown in Figs. 1–4, the coalition may limit trade impacts to products and services that leave the participating members. Thus, it is possible that groupings of regions with similar environmental profiles could form coalitions with binding commitments. Cooperation among regions and policies may face fewer obstacles and may be a more effective method of designing an optimal framework (Victor et al., 2005). Therefore, we suggest that one way to reduce the impact of trade on climate policy may be to encourage coalition formation to conduct cooperation.

In the end, it is not trivial to compare this study with some studies for the embodied CO_2 emissions in China conducted by previous researchers. As discussed in the introduction section, this paper thoroughly investigated methods to reduce the impact of trade on individual provinces. Although the coefficient between the EET and the primary industry or tertiary industry isn't significant, considering the negative sign, within the context of climate policy, encouraging related regions to develop primary industry or tertiary industries might be an alternative for stakeholders to reduce the impact of trade. However, more importantly, by providing knowledge regarding the emission profiles of possible regional coalitions, one of the important contributions of this study is to stimulate the trend of regional cooperation for carbon mitigation.

4 Conclusions

Based on multi-regional input–output analysis, China's provincial CO_2 emissions embodied in trade were calculated, and CO_2 emissions embodied in trade per unit of value of trade in 30 Chinese provinces and municipalities were analyzed. The main conclusions are as follows:

1) The results indicate that the amount of provincial CO_2 emissions embodied in trade is 3082.95 million tons, which accounted for approximately 60.02% of China's CO_2 emissions in 2007. Trade has an obvious impact on the volume of provincial CO_2 emissions in climate policy. In addition, the CO_2 EEI and EEE values differ widely for the 30 Chinese provinces and municipalities studied. Some provinces and municipalities with a greater EEI, such as Zhejiang, Jilin, Tianjin, and Beijing, also have a greater net input of embodied CO_2 emissions. Some provinces, such as Gansu, Inner Mongolia, Yunnan, and Xinjiang, not only have more EEE but also have a net output of embodied CO_2 emissions. The higher the EEE is the more obvious provincial CO_2 emissions affected by a production-based approach are. Therefore, for those provinces, such as Inner Mongolia and Gansu, the volume of CO_2 emissions will be

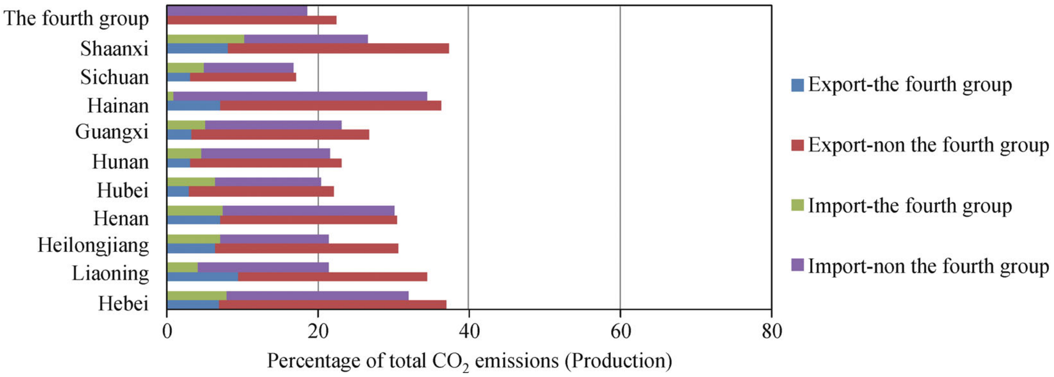

Fig. 4 EEE and EEI of the fourth group members, indicating the EET originating inside the coalition (left bar) and outside the coalition (right bar)

exaggerated under the production-based accounting principle, which may lead to greater CO_2 emissions reduction commitments being undertaken. Meanwhile, a high share of EEE affects not only competitiveness but also participation in binding emission reductions. However, for other provinces and cities with a net input of embodied CO_2 emissions and more CO_2 EEI, such as Zhejiang, Beijing, and Shanghai, where trade provides a mechanism to efficiently allocate resources in the process of economic development, environmental impacts, particularly for CO_2 emissions, have also been shifted. In addition, GDP, area, and secondary industry exhibit a positive impact on provincial EET, and only the variable GDP is statistically significant. The estimated coefficients for population, primary industry, and tertiary industry are both negative but not statistically significant.

2) According to the characteristics of the EET per unit of value of trade, the 30 Chinese provinces and cities studied are divided into four groups in this paper. The first group includes Beijing, Tianjin, Shanghai, Jiangsu, Zhejiang, and Guangdong. These provinces with more EEI are the net input of embodied CO_2 emissions, and the negative BEET is extremely large. Moreover, in this group, the EEE per unit of value of trade of a province’s exports is low, but the EEI per unit of value of trade of a province’s imports is extremely high. The second group consists of Jilin, Anhui, Fujian, Jiangxi, Shandong, and Chongqing. These provinces and cities are the net input of embodied CO_2 emissions, and the EEI per unit of value of trade of the provinces’ imports is high. The third group contains Guizhou, Xinjiang, Shanxi, Ningxia, Gansu, Yunnan, Inner Mongolia, and Qinghai. Their EET per unit of value of trade is extremely high. In addition, the eight provinces with more EEE are the net output of embodied CO_2 emissions, and the positive BEET is extremely large. Meanwhile, the EEE per unit of value of trade of a province’s exports is extremely high, but the EEI per unit of value of trade of a province’s imports remains relatively low. The fourth group includes Hainan, Heilongjiang, Shaanxi, Liaoning, Guangxi, Sichuan, Hubei, Hunan, Henan, and Hebei. Their EET per unit of value of trade is high. Moreover, these provinces are the net output of embodied CO_2 emissions, but the positive BEET is relatively small.

3) The EET of individual provinces is generally larger and more variable compared with that of the coalition as a whole. The coalition may limit trade impacts to products and services that leave the participating members. Thus, it is possible that groupings of regions with similar environmental profiles could form coalitions with binding commitments. Therefore, one way to reduce the impact of trade on climate policy may be to encourage coalition formation to conduct cooperation. Notably, however, the extent of reduction in a coalition varies in different provinces. Moreover, it is necessary that those provinces that benefit most should provide financial and technological aid to those provinces that suffer most or benefit least in climate policy.

Acknowledgements We thank the anonymous reviewers and the editor for their useful suggestions and valuable comments. Financial support from the National Basic Research Program of China (2012CB955800) is gratefully acknowledged.

References

Ahmad N, Wyckoff A (2003). Carbon dioxide emissions embodied in international trade of goods. Organisation for Economic Co-operation and Development. OECD, Paris

Amin A (1999). An institutionalist perspective on regional economic development. International Journal of Urban and Regional Research, 23(2): 365–378

Cendra J D (2006). Can emissions trading schemes be coupled with border tax adjustments? An Analysis vis‐à‐vis WTO Law1. Review of European Community and International Environmental Law, 15(2): 131–145

CESY (2008). China Energy Statistical Yearbook, National Bureau of Statistics of China, National Development and Reform Commission. China Statistics Press, Beijing, China(in Chinese)

Chen G Q, Chen H, Chen Z M, Zhang B, Shao L, Guo S, Zhou S Y, Jiang M M. (2011). Low-carbon building assessment and multi-scale input–output analysis. Communications in Nonlinear Science and Numerical Simulation, 16(1): 583–595

Chen G Q, Chen Z M (2010). Carbon emissions and resources use by Chinese economy 2007: a 135-sector inventory and input–output embodiment. Communications in Nonlinear Science and Numerical Simulation, 15(11): 3647–3732

Chen G Q, Chen Z M (2011a). Greenhouse gas emissions and natural resources use by the world economy: Ecological input-output modeling. Ecological Modelling, 222 (14): 2362–2376

Chen G Q, Guo S, Shao L, Li J S, Chen Z M. (2013). Three-scale input–output modeling for urban economy: Carbon emission by Beijing 2007. Communications in Nonlinear Science and Numerical Simulation, 18(9): 2493–2506

Chen G Q, Zhang B (2010). Greenhouse gas emissions in China 2007: inventory and input–output analysis. Energy Policy, 38: 6180–6193

Chen Z M, Chen G Q (2011b). Embodied carbon dioxide emission at supra-national scale: A coalition analysis for G7, BRIC, and the rest of the world. Energy Policy, 39: 2899–2909

Chen Z M, Chen G Q, Zhou J B, Jiang M M, Chen B. (2010a). Ecological input–output modeling for embodied resources and emissions in Chinese economy 2005. Communications in Nonlinear Science and Numerical Simulation, 15(7): 1942–1965

Chen Z M, Chen G Q, Chen B (2010b). Embodied carbon dioxide emissions of the world economy: a systems input-output simulation for 2004. Procedia Environmental Sciences, 2: 1827–1840

Chen Z M, Chen G Q (2013). Demand-driven energy requirement of world economy 2007: A multi-region input-output network simulation. Communications in Nonlinear Science and Numerical Simulation, 18(7): 1757–1774

Davis S J, Caldeira K (2010). Consumption-based accounting of CO_2

emissions. Proceedings of the National Academy of Sciences, 107 (12): 5687–5692

Dong Y L, Ishikawa M, Liu X B, Wang C. (2010). An analysis of the driving forces of CO_2 emissions embodied in Japan–China trade. Energy Policy, 38: 6784–6792

Fan G, Su M, Cao J (2010). An economic analysis of consumption and carbon emission responsibility. Economic Research, 1: 4–14(in Chinese)

Feenstra R C (2003). Advanced international trade: Theory and evidence; Princeton University Press: Princeton, N J

Gregg J S, Andres R J, Marland G (2008). China: Emissions pattern of the world leader in CO_2 emissions from fossil fuel consumption and cement production. Geophysical Research Letters, 35(8): L08806

Guo J, Zhang Z, Meng L (2012). China's provincial CO_2 emissions embodied in international and interprovincial trade. Energy Policy, 42: 486–497

Guo J, Zou L L, Wei Y M (2010). Impact of inter-sectoral trade on national and global CO_2 emissions: an empirical analysis of China and US. Energy Policy, 38: 1389–1397

IEA (2009). CO_2 emissions from fuel combustion 2009-highlights. Also available at: http: //www. iea.org/co2highlights/co2highlights.pdf. 2008

IPCC (2006). The 2006 IPCC guidelines for national greenhouse gas inventories (2006 guidelines). Also available at: http://www.ipcc-nggip.iges.or.jp/public/2006gl/index. html

Lenzen M, Pade L L, Munksgaard J (2004). CO_2 multipliers in multi-region input–output models. Economic Systems Research, 16(4): 391–412

Li J S, Alsaed A, Hayat T, Chen G Q. (2014). Energy and carbon emission review for Macao's gaming industry. Renewable and Sustainable Energy Reviews, 29: 744–753

Li Y, Hewitt C N (2008). The effect of trade between China and the UK on national and global carbon dioxide emissions. Energy Policy, 36: 1907–1914

Li F Y, Liu W D, Tang Z P (2013). Study on inter-regional transfer of embodied pollution in China. Acta Geographica Sinica, 68(6): 792–801(in Chinese)

Liang Q M, Fan Y, Wei Y M (2007). Multi-regional input–output model for regional energy requirements and CO_2 emissions in China. Energy Policy, 35: 1685–1700

Lin B, Sun C (2010). Evaluating carbon dioxide emissions in international trade of China. Energy Policy, 38: 613–621

Liu X, Ishikawa M, Wang C, Dong Y L, Liu W L. (2010). Analyses of CO_2 emissions embodied in Japan–China trade. Energy Policy, 38: 1510–1518

Liu W D, Chen J, Tang Z P, Liu H G, Han D, Li F Y. (2012). Theory and Practice for Building Multi-regional Input-output Table for 30 Provinces in China in 2007. Beijing: China Statisitics Press (in Chinese)

Liu Y H, Ge Q S, He F N (2008). Counter measures against international pressure of reducing CO_2 emissions and analysis on China's potential of CO_2 emission reduction. Acta eographica Sinica, 63(7): 675–682 (in Chinese)

Liu L, Ma X M (2011). CO_2 embodied in China's foreign trade 2007 with discussion for global climate policy. Procedia Environmental Sciences, 5, 105–113

Machado, G.V. Energy Use, CO_2 Emissions and Foreign Trade: an IO Approach Applied to the Brazilian Case. Thirteenth International Conference on Input–Output Techniques, Macerata, Italy. 21–25 Aug. 2000

Machado G, Schaeffer R, Worrell E (2001). Energy and carbon embodied in the international trade of Brazil: an input–output approach. Ecological Economics, 39(3): 409–424

Meng L, Guo J, Chai J, Zhang Z. (2011). China's regional CO_2 emissions: Characteristics, inter-regional transfer and emission reduction policies. Energy Policy, 39: 6136–6144

Munksgaard J, Pedersen K A (2001). CO_2 accounts for open economies: Producer or consumer responsibility. Energy Policy, 29: 327–334

National Bureau of Statistics of China (2009). China Statistical Yearbook 2008 (Internet). Accessed 2009. http://www.stats.gov.cn/tjsj/ndsj/2008/indexch.htm (in Chinese)

Pan J, Phillips J, Chen Y (2008). China's balance of emissions embodied in trade: approaches to measurement and allocating international responsibility. Oxford Review of Economic Policy, 24: 354–376

Park H C, Heo E (2007). The direct and indirect household energy requirements in the Republic of Korea from 1980 to 2000 – an input–output analysis. Energy Policy, 35: 2839–2851

Peters G P (2008). From production-based to consumption-based national emission inventories. Ecological Economics, 65(1): 13–23

Peters G P, Weber C L, Guan D, Hubacek K. (2007). China's growing CO_2 emissions—a race between increasing consumption and efficiency gains. Environmental Science and Technology, 41(17): 5939–5944

Peters G P, Hertwich E G (2008a). CO_2 embodied in international trade with implications for global climate policy. Environmental Science and Technology, 42(5): 1401–1407

Peters G P, Hertwich E G (2008b). Post-Kyoto greenhouse gas inventories: Production versus consumption. Climatic Change, 86 (1–2): 51–66

Qi Y, Li H M, Xu M (2008). Accounting embodied carbon in import and export in China. China Population, Resources and Environment, 18: 8–13(in Chinese)

Shao L, Chen G Q, Chen Z M, Guo S, Han M Y, Zhang B, Hayat T, Alsaedi A, Ahmad B. (2014). Systems accounting for energy consumption and carbon emission by building. Communications in Nonlinear Science and Numerical Simulation, 19(6): 1859–1873

Shi M J, Wang Y, Zhang Z Y, Zhou X. (2012). Regional Carbon Footprint and Inter-regional Transfer of Carbon Emissions in China. Acta Geographica Sinica, 67(10): 1327–1338(in Chinese)

Shui B, Harriss R C (2006). The role of CO_2 embodiment in US–China trade. Energy Policy, 34: 4063–4068

Su B, Huang H C, Ang B W, Zhou P. (2010). Input–output analysis of CO_2 emissions embodied in trade: The effects of sector aggregation. Energy Economics, 32(1): 166–175

Victor D G, House J C, Joy S (2005). A Madisonian approach to climate policy. Science, 309, 1820–1821

Wang T, Watson J (2007). Who owns China's carbon emissions? Tyndall Centre for Climate Change Research Sussex, UK

Wang Z, Zhang S, Wu J (2012). A new RICEs model with the global emission reduction schemes. Chinese Science Bulletin, 57(33): 4373–4380

Weber C L, Matthews H S (2007). Embodied environmental emissions in US international trade, 1997–2004. Environmental Science and Technology, 41(14): 4875–4881

Weber C L, Peters G P, Guan D, Hubacek K. (2008). The contribution of Chinese exports to climate change, Energy Policy, 36: 3572–3577

Wei B Y, Fang X Q, Wang Y (2011). The effects of international trade on Chinese carbon emissions. Journal of Geographical Sciences, 21(2): 301–316

Wiedmann T (2009). A review of recent multi-region input–output models used for consumption-based emission and resource accounting. Ecological Economics, 69(2): 211–222

Wiedmann T, Lenzen M, Turner K, Barrett J. (2007). Examining the global environmental impact of regional consumption activities—Part 2: Review of input–output models for the assessment of environmental impacts embodied in trade. Ecological Economics, 61 (1): 15–26

Xu M, Allenby B, Chen W Q (2009). Energy and air emissions embodied in China–U.S. Trade: eastbound assessment using adjusted bilateral trade data. Environmental Science and Technology, 43(9): 3378–3384

Yan Y F, Yang L K (2010). China's foreign trade and climate change: a case study of CO_2 emissions. Energy Policy, 38: 350–356

Yang Q, Chen G Q (2013). Greenhouse gas emissions of corn–ethanol production in China. Ecological Modelling, 252(10): 176–184

Zhang X P (2009). Carbon dioxide emissions embodied in China's foreign trade. Acta Geographica Sinica, 64(2): 234–242(in Chinese)

Zhang Z K, Guo J E, Anniwear A (2011). Determination of each province carbon dioxide reduction target based on embodied carbon dioxide emissions. China Population, Resources and Environment, 21(12): 15–21 (in Chinese)

Zhou S Y, Chen H, Li S C (2010). Resources use and greenhouse gas emissions in urban economy: ecological input–output modeling for Beijing 2002. Communications in Nonlinear Science and Numerical Simulation, 15(10): 3201–3231

AUTHOR BIOGRAPHIES

Zhangqi ZHONG is a Ph. D. candidate in cartography and geographic information systems at the Key Laboratory of Geographic Information Science, East China Normal University. He received his B.S. in geographical science from Hunan University of Science and Technology in 2009, and M.S. in human geography from East China Normal University in 2012. His research interests include geocomputation and policy simulation, E-mail address: zzqi111@163.com.

Rui Huang is a Ph. D. candidate in cartography and geographic information systems at the Key Laboratory of Geographic Information Science, East China Normal University. She received her B.S. in geographical information system from North China University of Water Resources and Electric Power in 2009. Her research interests include geocomputation and policy simulation, E-mail address: huangrui4420@163.com

Qinneng TANG is a Ph. D. candidate in management science and engineering at the Institute of Policy and Management, Chinese Academy of Sciences. He received his B.S. in information management and information systems from Lanzhou University in 2008, and M.S. in information science and engineering from Chinese Academy of Sciences in 2011. His research interest is computational economics. E-mail address: colintang973@gmail.com.

Xiaonan CONG is a Post doctorate at the Institute for Urban and Environmental Studies, Chinese Academy of Social Sciences. He received his B.S. in business management from China Agricultural University in 2006, and M.S. in cartography and geographic information systems from East China Normal University in 2009, and Ph. D. in management science and engineering from Chinese Academy of Sciences in 2012. His research interests include computational economics, urban information systems, and urban simulation. E-mail address: ben-carrie@163.com.

Zheng WANG is currently a Professor of geography and management at the Key Laboratory of Geographic Information Science, East China Normal University and Institute of Policy and Management, Chinese Academy of Sciences. He received his M.S., B.S. and Ph. D. from East China Normal University. His research interests include geocomputation, policy simulation, regional science, policy modeling and simulations, and computational economics. He has published more than 200 academic papers and edited 14 books, scientific proceedings, and software systems. E-mail address: wangzheng@casipm.ac.cn.