Energy Policy 42 (2012) 486–497

Contents lists available at SciVerse ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

China's provincial CO_2 emissions embodied in international and interprovincial trade

Ju'e Guo, Zengkai Zhang*, Lei Meng

School of Management, Xi'an Jiaotong University, Xi'an 710049, China

ARTICLE INFO

Article history:
Received 31 August 2011
Accepted 8 December 2011
Available online 13 January 2012

Keywords:
Embodied CO_2 emissions
Multi-regional IO model
CO_2 emissions accounting principle

ABSTRACT

Trades create a mechanism of embodied CO_2 emissions transfer among regions, causing distortion on the total emissions. As the world's second largest economy, China has a large scale of trade, which results in the serious problem of embodied CO_2 emissions transfer. This paper analyzes the characteristics of China's CO_2 emissions embodied in international and interprovincial trade from the provincial perspective. The multi-regional Input–Output Model is used to clarify provincial CO_2 emissions from geographical and sectoral dimensions, including 30 provinces and 28 sectors. Two calculating principles (production accounting principle and consumption accounting principle, Munksgaard and Pedersen, 2001) are applied. The results show that for international trade, the eastern area accounts for a large proportion in China's embodied CO_2 emissions. The sectors as net exporters and importers of embodied CO_2 emissions belong to labor-intensive and energy-intensive industries, respectively. For interprovincial trade, the net transfer of embodied CO_2 emissions is from the eastern area to the central area, and energy-intensive industries are the main contributors. With the largest amount of direct CO_2 emissions, the eastern area plays an important role in CO_2 emissions reduction. The central and western areas need supportive policies to avoid the transfer of industries with high emissions.

1. Introduction

With strong economic growth, China's CO_2 emissions grow quickly. China overtook the United States and became the world's largest emitter of CO_2 in 2007 (IEA, 2009). Facing increasing international pressure to take collaborative action on curbing CO_2 emissions, China pledged to cut CO_2 emissions per unit of GDP by 40–45% from the level of 2005 by 2020. And China's "12th Five-Year Plan" for national economic and social development set targets to cut CO_2 emissions intensity by 17% over the next five years (2011–2015). The CO_2 emissions reduction target will be allocated among China's provinces according to each province's CO_2 emissions level in the base year of 2005, which are affected by trade. It is of great significance to calculate the CO_2 emissions embodied in trade for assigning the task of CO_2 emissions reduction to different provinces.

Through international trade, significant environmental impacts can be shifted from one country to another (Li and Hewitt, 2008). More and more researches (Peters et al., 2007; Guan et al., 2008; Weber et al., 2008; Feng et al., 2009; Guan et al., 2009; Zhang, 2009a; Zhang et al., 2009) investigating the driving forces of CO_2 emissions in China have emerged recently, and it is pointed out that China's CO_2 emissions are largely driven by the rapid growth of export-orientated production. The literatures on China's CO_2 emissions embodied in international trade can be roughly divided into two types. The first type focuses on the changing trend of embodied CO_2 emissions in a period (Wang and Watson, 2007; Pan et al., 2008; Qi et al., 2008; Weber et al., 2008; Wei et al.,2009; 2011; Zhang, 2009b; Lin and Sun, 2010; Yan and Yang, 2010; Liu and Ma, 2011). In recent years, China's CO_2 emissions embodied in international trade have risen quickly with the increasing level of economic openness, and China has been a net exporter of embodied CO_2 emissions for most years. The problem of "carbon leakage" is becoming more and more serious. International trade is a main reason for the rise of China's CO_2 emissions, due to trade surplus and relatively high level of CO_2 emissions intensity. The second type focuses on the CO_2 emissions embodied in the international trade with certain countries (Shui and Harriss, 2006; Li and Hewitt, 2008; Xu, et al., 2009; Dong et al., 2010; Guo et al., 2010; Liu et al., 2010; Zhou, 2010). China is a net exporter of CO_2 emissions embodied in international trade with the majority of foreign nations, and China-US trade surplus is the major cause of embodied CO_2 emissions transfer.

Previous studies mainly analyze CO_2 emissions embodied in international trade from the national perspective, not reflecting regional diversity within the country. International trade has

* Corresponding author. Fax: +86 29 82665049.
E-mail address: zengkaizhang@sina.com (Z. Zhang).

0301-4215/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.enpol.2011.12.015

different impacts on CO_2 emissions in different regions. For example, there were obvious differences in regional CO_2 emissions during the financial crisis of 2008–2009, when China's exports decreased rapidly. Eastern and central areas experienced a decrease of annual growth rates of CO_2 emission. The growth rates of CO_2 emissions for eastern and central areas were 9.15% and 9.07%, respectively, in 2007. After 2007 the growth rates fell down quickly, which were 3.96%, 5.86% in 2008 and 3.95%, 4.30% in 2009. However, the decrease of exports did not have an obvious influence on western area's CO_2 emissions, the annual growth rates of which were 7.17%, 8.85% and 8.67% in 2007, 2008 and 2009. (The data is from our earlier paper, Meng et al., 2011.) So it has great significance to analyze the CO_2 emissions embodied in international trade from a provincial perspective.

In 1997, the provinces with higher CO_2 emissions were mainly concentrated in areas around North China, while the high emission areas spread from the eastern coastal area to the central area such as Neimeng, Henan, Hubei and Hunan, in 2007 (Meng et al., 2011). With the government paying more attention to environmental protection, more and more enterprises with high emissions are moving from the coastal area to the central and western areas, which do not have strict environmental protection laws and regulations. Coastal provinces shift CO_2 emissions to central and western provinces, through moving in high emission goods from central and western provinces. Interprovincial trade has an obvious impact on provincial CO_2 emissions, especially considering the fact that the scale of interprovincial trade is much larger than that of international trade.

Input–output analysis (Leontief, 1941), widely used in the calculation of embodied CO_2 emissions can be mainly divided into two types (Lin and Sun, 2010): single-regional IO model (Lenzen, 1998; Hertwich et al., 2002; Sánchez-Chóliz and Duarte, 2004; Kander and Lindmark, 2006; Peters and Hertwich, 2006a; Mäenpää and Siikavirta, 2007; Pan et al., 2008; Yan and Yang, 2010; Wei et al., 2011) and multi-regional IO model (Ahmad and Wyckoff, 2003; Lenzen et al., (2004); Sánchez-Chóliz and Duarte, 2004; Munksgaard et al., 2005; Peters and Hertwich, 2006b; Ackerman et al., 2007; Mäenpää and Siikavirta, 2007; Peters, 2007; Weber and Matthews, 2007; Wilting and Vringer, 2007; Peters, 2008; Hertwich and Peters, 2009; Davis and Caldeira, 2010; Wiedmann et al., 2010; Peters et al., 2011). Multi-regional IO model not only reflects the relationship between different sectors, but also the economic links between regions. Adopting the multi-regional IO model, we analyze CO_2 emissions embodied in international trade from a provincial perspective and calculate the CO_2 emissions embodied in interprovincial trade to investigate the transfer of embodied CO_2 emissions among provinces in 2002, and then we estimate the provincial CO_2 emissions levels in the base year of China's CO_2 emissions reduction target under both production and consumption principles.. From analyses of both international and interprovincial trade, we can panoramically describe and evaluate the characteristics of China's provincial emissions.

The rest of the paper is organized as follows. Section 2 introduces the calculation method and data preparation. Section 3 analyzes the calculation results of embodied CO_2 emissions. Section 4 presents a discussion on CO_2 emissions under different principles, and then estimates the provincial emissions in 2005. A description of uncertainties is given in Section 5, followed by conclusions in Section 6.

2. Methodology and data

2.1. Calculation method

Input–output analysis has recently become popular in the context of carbon footprint calculations (Turner et al., 2007; Wiedmann et al. 2007; Minx et al., 2009; Wiedmann, 2009; Wiedmann et al. 2011). The IO table of province r has the accounting balance of monetary flows:

$$x_i^r = a_{i1}^r x_1^r + a_{i2}^r x_2^r + \cdots + a_{in}^r x_n^r + y_i^r + m_i^r + mi_i^r - e_i^r - so_i^r \tag{1}$$

where x_i^r is the output of province r in sector i, y_i^r is the final consumption of province r in sector i, m_i^r is the import of province r in sector i, mi_i^r is the interprovincial import of province r in sector i, e_i^r is the export of province r in sector i, so_i^r is the interprovincial export of province r in sector i, $a_{ij}^r$is the direct consumption coefficient of province r. Let A^r be the matrix of coefficients a_{ij}^r, X^r be the vector of coefficients x_i^r, Y^r be the vector of coefficients y_i^r, M^r be the vector of coefficients m_i^r, MI^r be the vector of coefficients mi_i^r, E^r be the vector of coefficients e_i^r, and SO^r be the vector of coefficients so_i^r, then the expression for the balance becomes

$$X^r = A^r X^r + Y^r + M^r + MI^r - E^r - SO^r \tag{2}$$

The interprovincial trade components ($mi_i^r$and so_i^r) can also be expressed using trade flow between province r and other provinces.

$$mi_i^r = \sum_s ms_i^{sr} \tag{3}$$

$$so_i^r = \sum_s ms_i^{rs} \tag{4}$$

where ms_i^{sr} is the transfer from province s to province r in sector i. Let MS^{sr} be the vector of coefficients ms_i^{sr}, and then the equation can be expressed as

$$X^r = A^r X^r + Y^r + M^r + \sum_s MS^{sr} - E^r - \sum_s MS^{rs} \tag{5}$$

The output of province r can be expressed as

$$X^r = (1 - A^r)^{-1}(Y^r + M^r + \sum_s MS^{sr} - E^r - \sum_s MS^{rs}) \tag{6}$$

Given the direct CO_2 emissions coefficient in each sector f_i^r, and then the CO_2 emissions of province r in sector i can be expressed as

$$c_i^r = f_i^r x_i^r \tag{7}$$

Let F^r be the vector of coefficients f_i^r, and then the CO_2 emissions of province r can be expressed as

$$c^r = F^r (1 - A^r)^{-1} \left(Y^r + M^r + \sum_s MS^{sr} - E^r - \sum_s MS^{rs} \right) \tag{8}$$

where $F^r(1-A^r)^{-1}$ is the embodied CO_2 emissions coefficient; $F^r(1-A^r)^{-1}Y^r$ is the CO_2 emissions embodied in the final consumption of province r; $F^r(1-A^r)^{-1}M^r$ is the CO_2 emissions avoided through importing from other nations; $\sum F^r(1- A^r)^{-1}MS^{sr}$ is the CO_2 emissions avoided through interprovincial trade; $F^r(1-A^r)^{-1}E^r$ is the CO_2 emissions embodied in exports of province r; $\sum F^r(1-A^r)^{-1}MS^{rs}$ is the CO_2 emissions embodied in the interprovincial export of province r. When we calculate CO_2 emissions embodied in international trade, "domestic technology assumption (DTA)" is used in our paper, which assumes that the emissions factors of imported goods are the same as those used domestically (Weber et al., 2008). Then the CO_2 emissions embodied in international trade can be expressed as

$$cm^r = F^r(1-A^r)^{-1}M^r \tag{9}$$

$$ce^r = F^r(1-A^r)^{-1}E^r \tag{10}$$

where cm^r is the CO_2 emissions embodied in the import of province r; ce^r is the CO_2 emissions embodied in the export of province r. The CO_2 emissions embodied in trade between province r and province s

can be expressed as

$$cms^{rs} = F^r(1-A^r)^{-1}MS^{rs} \tag{11}$$

where cms^{rs} is the transfer of embodied CO_2 emissions between province r and province s. Then the CO_2 emissions embodied in interprovincial trade can be expressed as follows:

$$cmi^r = \sum_s cms^{sr} \tag{12}$$

$$cso^r = \sum_s cms^{rs} \tag{13}$$

where cmi^r is the CO_2 emissions embodied in the interprovincial imports of province r; cso^r is the CO_2 emissions embodied in the interprovincial exports of province r.

2.2. Data sources and preparation

Multi-regional IO tables and sectoral CO_2 emissions coefficients are required to apply the input–output analysis. We use the multi-regional IO tables of 2002 for China (Li et al., 2010) in this paper for several considerations. First, multi-regional IO tables of 2002 are the most recent and complete data about China's 30 provinces of all the published NRIO tables. Second, 2002 is close to the base year (2005) of China's CO_2 emissions reduction target, it is proper to analyze the characteristics of China's base year CO_2 emissions. Third, besides the data on import and export, the multi-regional IO tables also provide the data on China's 30-region trade for 42 sectors, which are important for the calculation of emissions embodied in interprovincial trade. Each sector's direct CO_2 emissions coefficient is calculated as CO_2 emissions per unit of output, which is needed to calculate embodied CO_2 emissions coefficients. Because there is no direct statistics of CO_2 emissions, we calculate emissions based on the energy statistics through the method provided in IPCC (2006). Sectoral energy consumption data are obtained from energy balance table of each province (CESY, 2003).

The number of sectors is different between provincial IO tables and energy balance tables. In the provincial IO tables there are 42 sectors, but in the energy balance tables there are only 6 sectors. There are two data treatment schemes according to the choice of sector levels. The first is to aggregate the IO data to the level that matches the energy consumption data, while the other is to disaggregate the energy consumption data to the level that matches the IO table (Su et al., 2010). The two ways both have their strengths and weaknesses (comparisons of the two schemes are presented in Section 5). In order to retain the information of IO data as much as possible, we disaggregate the energy balance table based on the final energy consumption of industry sub-sectors. According to the characteristics of the data, the energy consumption data are disaggregated into 28 sectors. More specifically, the industry sector is disaggregated into 23 industry sub-sectors.

Provinces are divided into four types based on the calculation of CO_2 emissions intensities of industry sub-sectors. For the first type, it is calculated according to the major energy consumption of each sector in 2002. Provinces of the first type include Beijing, Tianjin, Shanxi, Neimeng, Liaoning, Jilin, Anhui, Fujian, Jiangxi, Henan, Hunan, Chongqing, Guizhou, Shaanxi, Gansu, Qinghai, Ningxia and Xinjiang. The second type does not have statistics on the major energy consumption of each sector in 2002, so we calculate emissions intensity according to each sector's major energy consumption of the neighboring year. Provinces of the second type include Heilongjiang, Zhejiang, Shandong and Yunnan. Provinces of the third type include Hebei and Guangdong, and only have statistics of each sector's total energy consumption. We estimate the emissions intensity according to total energy consumption. Provinces of the fourth type do not have statistics on sectoral energy consumption. We can only estimate the emissions intensity according to CO_2 emissions characteristics of another province with similar economic structure. Provinces under this principle include Shanghai, Jiangsu, Hubei, Guangxi, Hainan and Sichuan. The energy consumption data are from the Statistical Yearbook of each province.

China is geographically divided into eastern, central and western areas. In this paper, 30 provinces are analyzed (shown in Fig. 1). Liaoning, Hebei, Beijing, Tianjin, Shandong, Jiangsu, Shanghai, Zhejiang, Fujian, Guangdong, Guangxi and Hainan belong to the eastern area. Shanxi, Neimeng, Jilin, Heilongjiang,

Fig. 1. Map of China's provinces.

Anhui, Jiangxi, Henan, Hubei and Hunan are located in the central area. Chongqing, Sichuan, Guizhou, Yunnan, Shaanxi, Gansu, Qinghai, Ningxia and Xinjiang are all western provinces. Tibet, Hong Kong, Macau and Taiwan are not analyzed for the problem of data acquisition.

3. CO_2 emissions embodied in trade

3.1. CO_2 emissions embodied in international trade

CO_2 emissions embodied in international trade are calculated by Eqs. (9) and (10). In 2002, China's CO_2 emissions embodied in exports are 688.15 million tons, which are similar to the results of some previous studies (Peters and Herwich, 2008 (586.50 million tons); Weber et al., 2008 (760 million tons); Yan and Yang, 2010 (458.46 million tons)). Wei et al. (2011) claims that the proportion of domestic exported emissions in domestic emissions is 23.97% (20.26% in our paper). Emissions avoided through importing from other nations are 626.81 million tons. It should be pointed out that "DTA" will cause an overestimation of CO_2 emissions embodied in imports, for China has higher carbon intensity than that of supplying regions (Andrew et al., 2009). For example, Yan and Yang (2010) estimate that China's CO_2 emissions embodied in imports of 2002 are only 242.98 million tons, in which China's imports CO_2 emission factors are based on the US input–output table. In this section, provincial CO_2 emissions embodied in international trade are analyzed from geographical, sectoral and comprehensive perspectives.

3.1.1. Geographical analysis

Each province's CO_2 emissions embodied in international trade are presented in Fig. 2. The abbreviated name of each province is provided in Appendix A.

Since the reform and opening-up in 1978, the eastern area has achieved rapid economic development and great economic openness owing to location and policy advantages. The eastern area accounts for a large share of China's international trade, so CO_2 emissions embodied in international trade of eastern area are much higher than those of the central and western areas. Most provinces of the eastern area are net exporters of embodied CO_2 emissions, except four provinces: Beijing, Tianjin, Shanghai and Hainan. These four provinces have large percentage of service industries, and industrial products are mainly obtained through trade with other nations or provinces, so CO_2 emissions embodied in imports are higher than emissions embodied in exports. International trade contributes to emissions reduction of these four provinces.

Due to the influence of different factors, such as geographical condition and historical development, there is a big gap between the eastern area and the central western area in economic development. The central and western areas have lower level of economic openness than the eastern area, so the embodied CO_2 emissions of the central and western areas account for a very small percentage of China's embodied CO_2 emissions. There also exist five provinces (Neimeng, Jilin, Hubei, Shaanxi and Xinjiang) as net importers of embodied CO_2 emissions. These five provinces have less developed economy, limited by the low degree of economic openness. The CO_2 emissions levels of these provinces do not increase with international trade.

From a geographical perspective, there exist great regional differences in CO_2 emissions embodied in international trade, and the eastern area has larger scale of embodied CO_2 emissions than the central and western areas.

3.1.2. Sectoral analysis

Fig. 3 presents each sector's CO_2 emissions embodied in international trade. The embodied CO_2 emission of one sector is

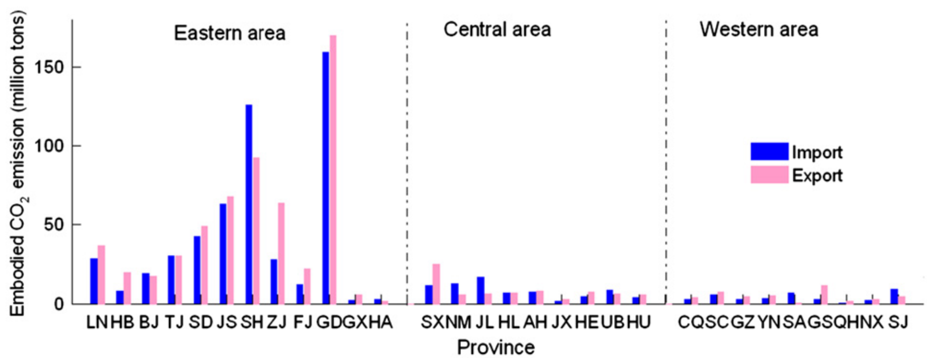

Fig. 2. CO_2 emissions embodied in international trade of China's 30 provinces.

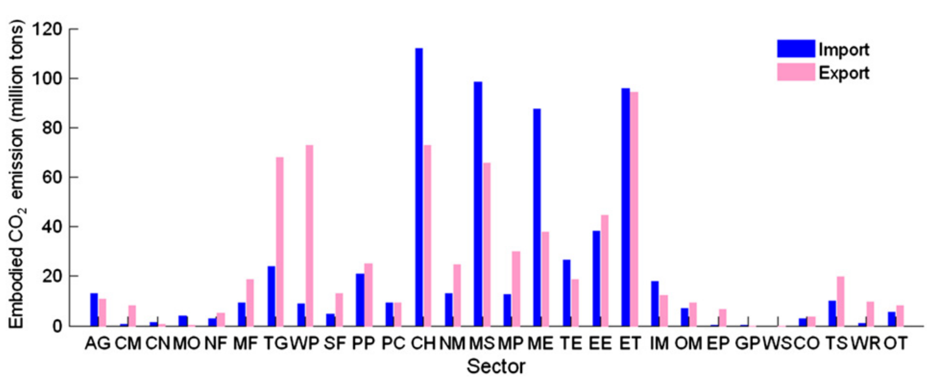

Fig. 3. CO_2 emissions embodied in international trade of 28 sectors.

the total sectoral emissions of all the provinces. The abbreviated name of each sector is provided in Appendix B.

Fig. 3 shows that CO_2 emissions embodied in international trade mainly concentrate on the secondary industry. The reasons are listed as follows. First, relying on the advantage of cheap labor force, China becomes the world manufacturing factory, and industrial products hold a large proportion in China's international trade. Second, the secondary industry has a much higher CO_2 emissions intensity than those of the primary and tertiary industries. The same amount of foreign trade corresponds to larger embodied CO_2 emissions.

Most of the sectors as net exporters of embodied CO_2 emissions are labor-intensive industries, such as TG (textile goods) and WP (wearing apparel, leather, furs, down and related products), and the sectors as net importers are mainly energy-intensive industries, such as CH (chemicals), MS (metals smelting and pressing) and ME (machinery and equipment). The sectoral characteristics of net embodied CO_2 emissions are mainly determined by the composition of foreign merchandise trade. China mainly exports labor-intensive products and raw products and imports advanced technology, key equipment and component, important energy resources and raw materials. So sectors as net importers and exporters are centered on different industries.

From a sectoral perspective, China's international trade structure determines the sectoral characteristics of China's embodied CO_2 emissions. The secondary industry accounts for a large proportion in embodied CO_2 emissions, and sectors as net exporters and importers of embodied CO_2 emissions belong to labor-intensive and energy-intensive industries respectively.

3.1.3. Comprehensive analysis

Three area's sectoral CO_2 emissions embodied in international trade are shown in Fig. 4. The sectoral embodied CO_2 emission of an area is the total sectoral emissions of all the provinces located in this area.

There exists disequilibrium of international trade development level and mode among three areas. The eastern area is the most developed region of China and has reasonable economic structure and trade structure compared with the central and western areas, so the embodied CO_2 emissions of eastern area are dispersed in several sectors. The central and western areas have relatively low levels of economic openness and single foreign trade structure; hence the embodied CO_2 emissions concentrate on only a few industry sub-sectors, including CH (chemicals), MS (metals smelting and pressing) and ME (machinery and equipment).

China is a net exporter of CO_2 emissions embodied in international trade, while there are great differences in sectors as net exporters of embodied emissions among different areas. In the eastern area, labor-intensive industries are the main contributors to economic development and account for a large proportion in foreign trade. Sectors of labor-intensive industries are the main net exporters of embodied CO_2 emissions, such as TG (textile goods) and WP (wearing apparel, leather, furs, down and related products). The sectors as net exporters of embodied CO_2 emissions of the central and western areas are energy-intensive industries, such as MS (metals smelting and pressing). It is consistent with the fact that energy-intensive industries hold a large proportion in the central and western areas, as China's important energy base. It should be pointed out that although China is a net exporter of embodied CO_2 emissions, there are some sectors whose CO_2 emissions embodied in import are larger than export, such as ME (machinery and equipment). It reflects the fact China's manufacturing industry mainly produces low-end products, and technology level in the manufacturing industry is low. Equipments for general use and special purpose are mainly imported from abroad.

From a comprehensive perspective, there exist great geographical differences in sectoral characteristics of embodied CO_2 emissions among three areas. The eastern area's embodied CO_2 emissions are dispersed in several sectors, while embodied CO_2 emissions concentrate on only a few sectors in central and western areas. Labor-intensive and energy-intensive sectors are the main contributors to exports of embodied CO_2 emissions for the eastern area and the central western area, respectively.

3.2. CO_2 emissions embodied in interprovincial trade

CO_2 emissions embodied in interprovincial trade are calculated by Eqs. (12) and (13). In 2002, China's CO_2 emissions embodied in interprovincial trade are 2181.48 million tons, which are much larger than those embodied in international trade. In this section, provincial CO_2 emissions embodied in interprovincial trade are also analyzed from geographical, sectoral and comprehensive perspectives.

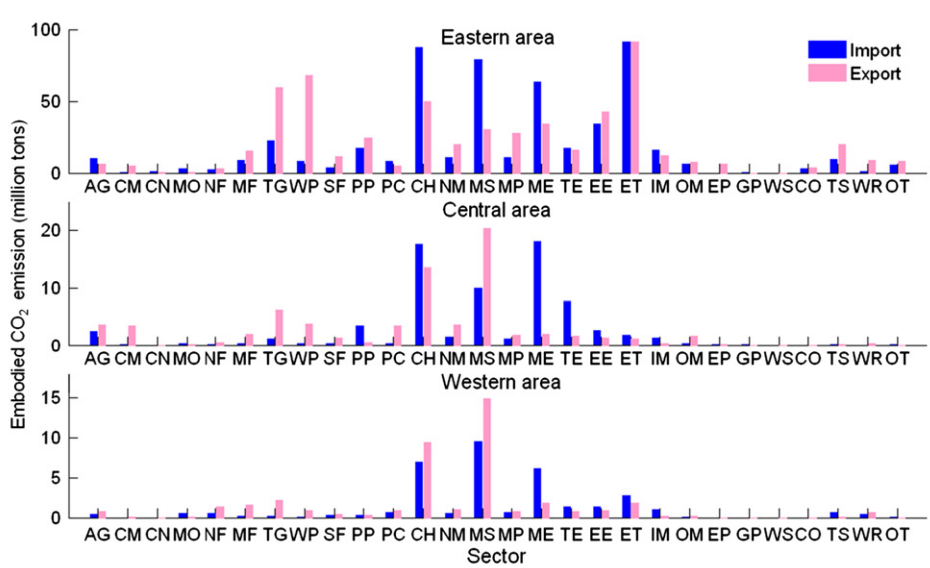

Fig. 4. Sectoral CO_2 emissions embodied in international trade of three areas.

3.2.1. Geographical analysis

Each province's CO_2 emissions embodied in interprovincial trade are shown in Fig. 5.

The reform and open policy drives China's quick economic development, while the imbalance of economic growth among different areas becomes more remarkable. From eastern area to western area, the level of economic development declines obviously. The trade amount is closely related to the level of economic development, so the level of CO_2 emissions embodied in interprovincial trade has the same changing trend. For example, embodied CO_2 emissions of the western area are the smallest, which has a low level of economic development and openness. With large embodied CO_2 emissions, the eastern and central areas' CO_2 emissions are affected by the interprovincial trade more obviously. Fig. 5 shows that most provinces of the eastern area are net input of embodied CO_2 emissions, while most provinces of the central area are net output of embodied CO_2 emissions. It reflects that the net transfer of embodied CO_2 emissions is from the eastern area to the central area. Interprovincial trade increases the burden of CO_2 emissions reduction for the central area, as the receiver of high emissions industries transferred from developed regions.

From a geographical perspective, there is a decreasing trend in CO_2 emissions embodied in interprovincial trade from the eastern to the western area, and the net transfer of embodied CO_2 emissions is from the eastern area to the central area.

3.2.2. Sectoral analysis

Fig. 6 presents each sector's CO_2 emissions embodied in interprovincial trade. The embodied CO_2 emission of one sector is the total sectoral emissions of all the provinces. The total sectoral emissions embodied in interprovincial import are equal to those of interprovincial export, so we do not differentiate between the sectoral CO_2 emissions embodied in interprovincial import and export.

Fig. 6 shows that embodied CO_2 emissions of the secondary industry are much higher than those of the primary and tertiary industry. The industry sectors are the main contributors to the CO_2 emissions embodied in interprovincial trade. It reflects the industrial products account for a large proportion in China's interprovincial trade and the CO_2 emissions intensity of the secondary industry is higher. In the secondary industry, the sector MS (metals smelting and pressing) has the highest embodied CO_2 emissions. With fast economic development, China's steel production and consumption increase rapidly, driven by massive infrastructure construction. China becomes the world's largest producer and consumer of iron and steel. Active steel market results in the large amount of CO_2 emissions embodied in interprovincial trade in sector MS, which is also a typical high emissions sector.

From a sectoral perspective, embodied CO_2 emissions concentrate on only a few sectors, and the industry sectors especially the sector MS account for a large proportion in China's CO_2 emissions embodied in interprovincial trade.

3.2.3. Comprehensive analysis

Three areas' sectoral CO_2 emissions embodied in interprovincial trade are shown in Fig. 7.

Most sectors of the eastern area are net input of CO_2 emissions embodied in interprovincial trade, and most sectors of the central area are net output of CO_2 emissions embodied in interprovincial trade. It also reflects that the net transfer of embodied CO_2 emissions between the eastern and central areas is from the eastern area to the central area. Fig. 7 shows that energy intensive sectors account for a higher proportion in the net transfer of embodied CO_2 emissions, such as CM (coal mining and processing), MS (metals smelting and pressing), and EP (electricity steam and hot water production and supply). As China's energy base, the central area provides energy to support the economic

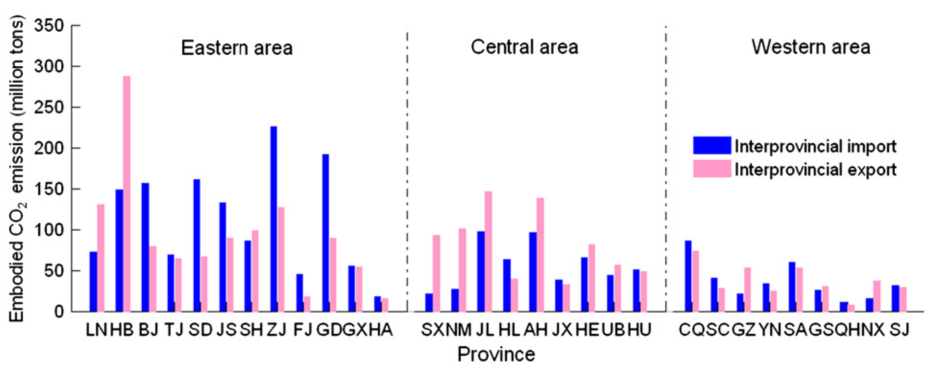

Fig. 5. CO_2 emissions embodied in interprovincial trade of China's 30 provinces.

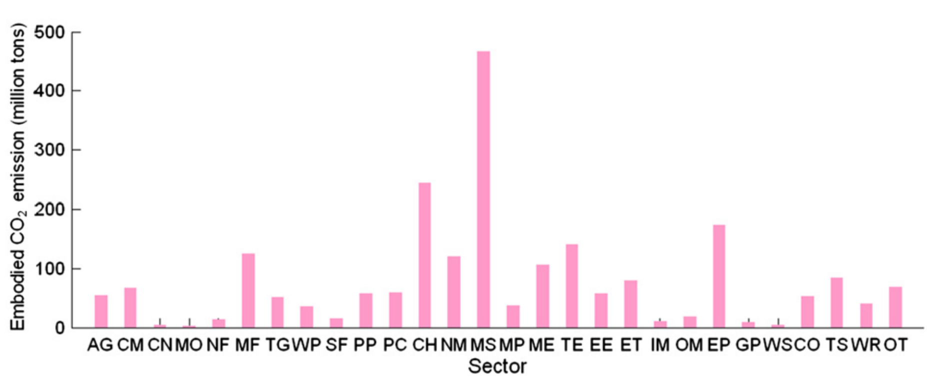

Fig. 6. CO_2 emissions embodied in interprovincial trade of 28 sectors.

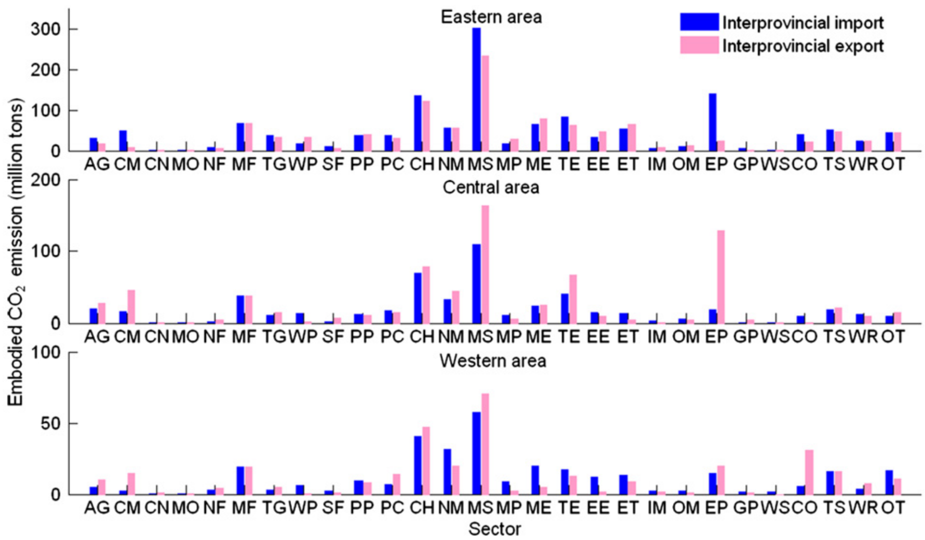

Fig. 7. Sectoral CO_2 emissions embodied in interprovincial trade of three areas.

development of the eastern area. So energy intensive sectors are the main contributors to the net transfer of embodied CO_2 emissions.

The western area has both sectors as net input and output of embodied CO_2 emissions. However the sectors as net input of embodied CO_2 emissions belong to manufacturing industry and the sectors as net output of embodied CO_2 emissions belong to energy intensive industry. The western area also has abundant energy, and energy intensive industries hold a large proportion in the economy of the western area. However the manufacturing industry is less developed, so manufacturing products are mainly moved in from other provinces.

From a comprehensive perspective, the energy intensive sectors are the main contributors to the net transfer of CO_2 emissions embodied in interprovincial trade, and the inverse distribution of production and consumption of energy results in the net transfer direction of embodied CO_2 emissions.

4. Discussion on provincial CO_2 emissions under different principles

In this section, we compare CO_2 emissions under two different emission accounting principles and estimate the provincial CO_2 emissions levels in the base year of China's CO_2 emissions reduction target under two principles, which are of great significance for determining regional CO_2 emissions reduction strategies and targets.

4.1. Comparison of CO_2 emissions under two different principles

According to whether embodied CO_2 emissions are considered, there are two CO_2 emissions accounting principles: "production accounting principle" and "consumption accounting principle" (also known as "carbon footprint accounting"). Under the production accounting principle the producer is responsible for the CO_2 emissions from the production of energy, goods and services; while under the consumption accounting principle the consumer undertake the responsibility (Munksgaard and Pedersen, 2001; Bastianoni et al., 2004; Peters and Hertwich, 2006a; Wiedmann et al., 2010). Production based CO_2 emissions of 2002 are calculated based on the final energy consumption data through the method provided by IPCC (2006). Our earlier paper (Meng et al., 2011) describes the method in detail, and calculates the CO_2 emissions of 30 provinces from 1997 to 2009. The relationship between CO_2 emissions of province r under production accounting principle c_p^r and those under consumption accounting principle c_c^r is shown as follows:

$$c_c^r = c_p^r + cm^r + cmi^r - ce^r - cso^r \tag{14}$$

where c_c^r is the CO_2 emission of province r under consumption accounting principle; c_p^r is the CO_2 emission of province r under production accounting principle; cm^r is the CO_2 emission embodied in import of province r; ce^r is the CO_2 emission embodied in export of province r; cmi^r is the CO_2 emission embodied in products moved to province r from other provinces; cso^r is the CO_2 emission embodied in products sent to other provinces from province r. It should be pointed out that the equation includes both international and interprovincial trade.

Fig. 8 shows each province's CO_2 emissions under two different accounting principles in 2002.

There is a decreasing trend of CO_2 emissions from the eastern area to the western area under production accounting principle. As the most developed region of China, the eastern area takes the largest proportion of China's CO_2 emissions. The top 3 provinces with largest CO_2 emissions are Hebei, Shanxi and Shandong, which are all located in North China. It reflects that there are large regional differences in China's CO_2 emissions. Regional CO_2 emissions reduction targets should be customized to promote the achievement of China's total CO_2 emissions reduction target.

The consumption accounting principle further emphasizes the eastern area's responsibility for CO_2 emissions. Most eastern provinces' CO_2 emissions increase when the accounting principle is changed to the consumption accounting principle, because the eastern area is net input of CO_2 emissions embodied in interprovincial trade. These provinces avoid CO_2 emissions through consuming goods which are produced in other provinces. Under consumption accounting principle, the top 5 provinces with the highest CO_2 emission are mainly centered in coastal area, including Shandong, Guangdong, Jiangsu, Zhejiang and Henan. The five provinces are also the top 5 provinces with the largest GDP, and have better ability of emissions reduction for better economic conditions and advanced technologies. Eliminating the effect of trade, the consumption accounting principle accurately reflects the provincial contribution to China's CO_2 emissions.

The provinces whose CO_2 emissions levels are affected most remarkably by the principle are Beijing and Hebei, and their CO_2 emissions change by 119.85% and −54.56%, respectively, when

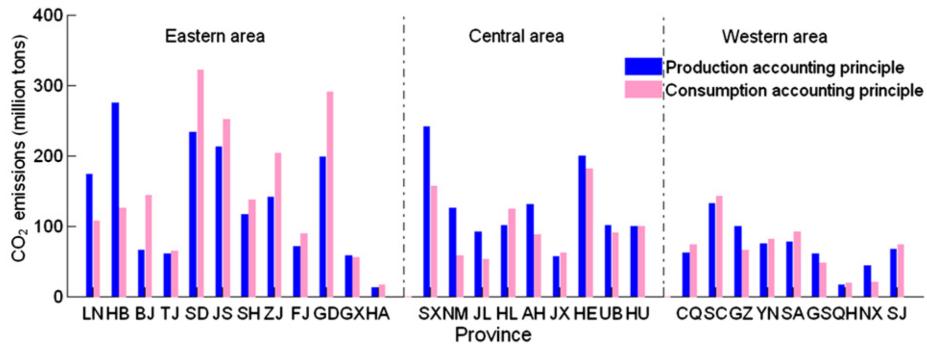

Fig. 8. Provincial CO_2 emissions under different principles in 2002.

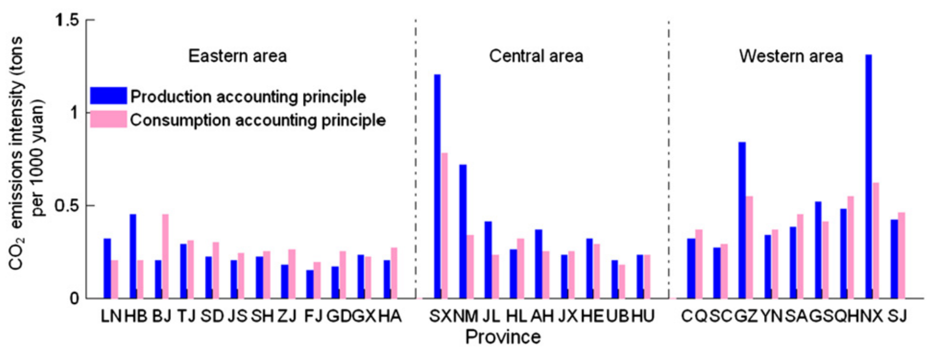

Fig. 9. Provincial CO_2 emissions intensity under different principles in 2002.

the principle is changed from production accounting principle to consumption accounting principle. Beijing is surrounded by Hebei, and the economic links between them are strong. Large amounts of goods are moved from Hebei to Beijing, especially goods from high energy consumption and high emissions sectors, so the CO_2 emissions of these two provinces change obviously.

Fig. 9 shows each province's CO_2 emissions intensity (CO_2 emissions per unit of GDP) under two different accounting principles in 2002.

The eastern area has strict environmental protection laws and regulations, advanced emission-cutting technologies and developed modern service industries, so the direct CO_2 emissions intensities of the eastern area are lower than those of central and western areas. The economic development modes of the central and western areas are characterized by high energy consumption and high emissions. Facing the double tasks of developing economy and reducing CO_2 emissions, the central and western areas should be paid more attention in the process of CO_2 emissions reduction, especially provinces as China's energy base, such as Ningxia, Shanxi, Guizhou and Neimeng.

The consumption accounting principle diminishes the differences in CO_2 emissions among different regions. There is a slight increase in CO_2 emissions intensities for coastal provinces, and CO_2 emissions intensities of provinces as China's energy base decrease remarkably. For example, the CO_2 emissions intensity of Ningxia is very high under production accounting principle. However, there will be fewer differences between Ningxia and other provinces under consumption accounting principle.

In sum, CO_2 emissions accounting principles have an obvious impact on the volume and intensity of provincial CO_2 emissions. The impacts on the emissions volume of the eastern area and the CO_2 emissions intensities of provinces as China's energy base are much more obvious. China should set provincial emissions reduction targets under comprehensive consideration of regional CO_2 emissions based on different principles.

4.2. China's provincial emissions in the base year of CO_2 emissions reduction target

In November 2009, China pledged to cut CO_2 emissions with 2005 as the base year. Regional CO_2 emissions levels of 2005 are of great significance for determining regional CO_2 emissions reduction strategies and targets. In this section we estimate China's base year CO_2 emissions levels under both production and consumption accounting principles.

Provincial production based CO_2 emissions are calculated based on the provincial final energy consumption of 2005 with the same calculation method as 2002. There are no multi-regional IO tables of 2005, so we estimate embodied CO_2 emissions and calculate the consumption based CO_2 emissions.

The CO_2 emissions of province r under consumption accounting principle of 2005 can be calculated as follows:

$$c^r_{c2005} = c^r_{p2005} + cm^r_{2005} + cmi^r_{2005} - ce^r_{2005} - cso^r_{2005} \tag{15}$$

The terms in the Eq. (15) are similar to those of Eq. (14). Please refer to the paragraph under Eq. (14) for detailed explanations. The CO_2 emissions embodied in imports of 2005 are estimated as follows:

$$cm^r_{2005} = cm^r_{2002} \frac{m^r_{2005}}{m^r_{2002}} \frac{ci^r_{2005}}{ci^r_{2002}} \frac{cpi^r_{2002}}{cpi^r_{2005}} \frac{er_{2002}}{er_{2005}} \tag{16}$$

where cm^r is the CO_2 emission embodied in import of province r; m^r is the import of province r; ci^r is the CO_2 emissions intensity of province r. The fuel mix and technology used have changed, it is necessary to update the CO_2 emissions intensity. cpi^r is the consumer price index of province r. Import is adjusted by CPI to update the economic information. er is the exchange rate of a US dollar relative to Chinese currency RMB. The import is also adjusted by exchange rate, for international trade is denominated in US dollars. The CO_2 emissions embodied in exports of 2005 are calculated as follows:

$$ce^r_{2005} = ce^r_{2002} \frac{e^r_{2005}}{e^r_{2002}} \frac{ci^r_{2005}}{ci^r_{2002}} \frac{cpi^r_{2002}}{cpi^r_{2005}} \frac{er_{2002}}{er_{2005}} \quad (17)$$

where ce^r is the CO_2 emission embodied in export of province r; e^r is the export of province r.

Since data on interprovincial trade of 2005 are not available, we estimate the CO_2 emissions embodied in interprovincial trade by defining a transfer coefficient t^{sr} as follows:

$$t^{sr} = \frac{cms^{sr}}{c^r_p} \quad (18)$$

Table 1
China's base year (2005) CO_2 emissions.

Province	PAP		CAP	
	CO_2 emissions (million tons)	CO_2 emissions intensity (tons/1000 Yuan)	CO_2 emissions (million tons)	CO_2 emissions intensity (tons/1000 Yuan)
Beijing	78.87	0.11	184.77	0.27
Tianjin	82.29	0.21	90.84	0.23
Hebei	438.42	0.44	180.25	0.18
Shanxi	281.64	0.67	177.63	0.42
Neimeng	250.36	0.64	161.84	0.41
Liaoning	218.39	0.27	118.46	0.15
Jilin	130.51	0.36	82.74	0.23
Heilongjiang	127.83	0.23	156.95	0.28
Shanghai	148.14	0.16	152.21	0.16
Jiangsu	382.25	0.21	430.72	0.23
Zhejiang	222.49	0.17	291.65	0.22
Anhui	146.39	0.27	86.65	0.16
Fujian	129.24	0.20	141.94	0.22
Jiangxi	85.20	0.21	91.41	0.23
Shandong	531.10	0.29	676.57	0.37
Henan	357.18	0.34	327.19	0.31
Hubei	205.01	0.31	193.76	0.29
Hunan	186.39	0.28	184.96	0.28
Guangdong	311.37	0.14	425.11	0.19
Guangxi	92.49	0.23	86.22	0.22
Hainan	14.96	0.17	26.48	0.29
Chongqing	79.44	0.23	96.66	0.28
Sichuan	183.58	0.25	202.30	0.27
Guizhou	170.11	0.85	121.00	0.60
Yunnan	140.24	0.41	153.18	0.44
Shaanxi	125.18	0.32	147.64	0.38
Gansu	83.39	0.43	65.15	0.34
Qinghai	20.35	0.37	23.53	0.43
Ningxia	56.07	0.92	25.23	0.41
Xinjiang	86.49	0.33	89.31	0.34

Notes: PAP stands for the production accounting principle; CAP stands for the consumption accounting principle.

Because it is a short interval of time between 2002 and 2005, the economic structure and trade structure do not change significantly. We estimate the transfer of embodied CO_2 emissions of 2005 based on the transfer coefficient of 2002. The CO_2 emissions embodied in interprovincial trade of 2005 are shown as follows:

$$cms^{sr}_{2005} = t^{sr}_{2002} c^r_{2005} \quad (19)$$

$$cmi^r_{2005} = \sum_s cms^{sr}_{2005} \quad (20)$$

$$cso^r_{2005} = \sum_s cms^{rs}_{2005} \quad (21)$$

Each province's base year CO_2 emissions under production and consumption accounting principles are shown in Table1.

Provincial CO_2 emissions under production accounting principle accurately reflect the geographical distribution of China's direct CO_2 emissions, while provincial CO_2 emissions under consumption accounting principle accurately reflect the provincial contribution to CO_2 emissions. The coastal area accounts for a large proportion of China's CO_2 emissions and is the main contributor to emissions. Coastal provinces play important roles in China's CO_2 emissions reduction. Although the inland area has lower level of CO_2 emissions, it has higher CO_2 emissions intensity. Reducing the CO_2 emissions intensities of the inland provinces is of great significance for China's CO_2 emissions reduction.

In a word, both production and consumption based CO_2 emissions levels in base year are important for the determination of provincial CO_2 emissions reduction targets. China's CO_2 emissions reduction target should be allocated among provinces, based on comprehensive consideration of regional CO_2 emissions level under both production and consumption accounting principles.

5. Aggregation uncertainty analysis

Multi-regional IO models not only inherit all uncertainties specific to single region IO analysis, but also introduce additional uncertainties (Thomas, 2009). Some studies have tried to quantify error margins. For example, Lenzen et al. (2010) attempt to capture all possible variations of the whole MRIO model using Monte Carlo techniques. Thomas (2009) gives a detailed review of relative studies, and points out that "aggregation is a problem in particular when high and low impacting sectors are combined in one aggregated sector". Wyckoff and Roop (1994) conduct a sensitivity analysis of aggregation bias ranging from 6 to 33 sectors for six OECD countries and report more than 30% difference between two estimates. Aggregation uncertainty has a significant effect on the calculation of embodied CO_2 emissions (Weber, 2008; Thomas, 2009; Su et al., 2010).

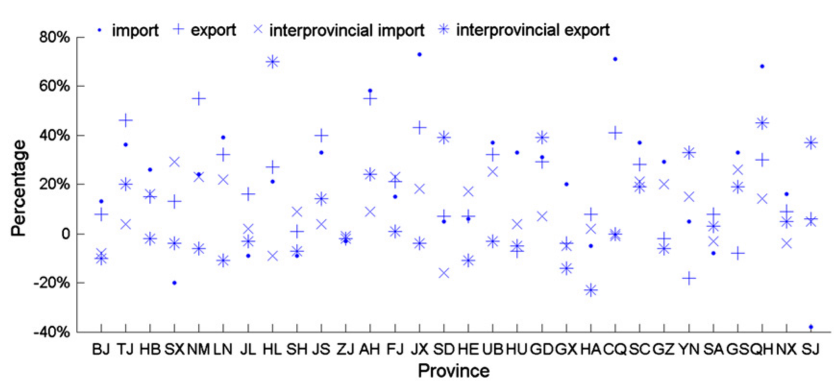

Fig. 10. Percentage change of each province's embodied CO_2 emissions.

Su et al. (2010) point out that levels around 40 sectors appear to be sufficient to capture the overall share of emissions embodied in a country's exports, and there is no significant difference when the sector is only 28. So we choose the aggregation level of 28 sectors. However, it also has great significance to analyze the different impacts of aggregation level on CO_2 emissions embodied in China's international and interprovincial trade, which has not been analyzed in previous studies. In this paper, we quantitatively calculate the percentage change of embodied CO_2 emissions of each province (shown in Fig. 10), when the sectors are aggregated into 6 according to the energy balance tables.

Fig. 10 shows that the aggregation level has an obvious impact on the calculation of embodied CO_2 emissions. When the sectors are aggregated into 6, CO_2 emissions embodied in trade will be averagely overestimated than the case with 28 sectors. It is consistent with the result of Su et al. (2010). The results also show that the impact of aggregation level on CO_2 emissions embodied in international trade (average percent changes of CO_2 emissions embodied in import and export are 21.22% and 17.87%) is larger than those embodied in interprovincial trade (average percent changes of CO_2 emissions embodied in interprovincial import and export are 8.91% and 8.53%).

Besides aggregation uncertainty, there are other uncertainties resulted from data and methodology. First, statistical data on each province's CO_2 emissions are lacking, let alone the sectoral CO_2 emissions of each province. We calculate the CO_2 emissions based on final energy consumption. The calculation result of China's CO_2 emissions of 2002 is 3396.19 million tons, which is slightly larger than the IEA estimation (3348.26 million tons) (IEA, 2010). Second, the domestic technology assumption will cause some overestimation of CO_2 emissions embodied in import. Third, the embodied CO_2 emissions of 2005 are calculated based on transfer coefficients of 2002, with the assumption that there are no obvious differences in economic structure and trade structure between 2002 and 2005. Facing those uncertainties in data and methodology, the results of embodied CO_2 emissions should be regarded as approximate. However the transfer direction of embodied CO_2 emissions is unlikely to be affected extremely by these uncertainties.

6. Conclusions

This paper analyzes China's CO_2 emissions embodied in international and interprovincial trade from geographical, sectoral and comprehensive perspectives and estimates each province's CO_2 emissions under two different principles. The main conclusions are shown as follows.

(1) There exist great geographical and sectoral differences in China's CO_2 emissions embodied in international trade. The secondary industry is the main contributor to embodied CO_2 emissions for the eastern area, which accounts for a large proportion in China's embodied CO_2 emissions, and sectors as net exporters and importers of embodied CO_2 emissions belong to labor-intensive and energy-intensive industries respectively. The central and western areas have low level of embodied CO_2 emissions, which concentrate on a few industry sub-sectors. (2) There is a decreasing trend in CO_2 emissions embodied in interprovincial trade from the eastern area to the western area, and the net transfer of embodied CO_2 emissions is mainly from the eastern area to the central area. Interprovincial trade increases the less-developed regions' burden for CO_2 emissions reduction. The energy intensive sectors, especially the sector metals smelting and pressing, account for a large proportion in embodied CO_2 emissions. (3) The production based CO_2 emissions accurately reflect the geographical distribution of China's direct CO_2 emissions. The coastal provinces account for a larger proportion of China's CO_2 emissions, and the inland provinces have higher direct CO_2 emissions intensities. The consumption based provincial CO_2 emissions eliminate the impact of trade on regional CO_2 emissions and reflect the provincial contribution to China's CO_2 emissions. The eastern area plays an important role in China's CO_2 emissions reduction, while the central and western areas need supportive policies on CO_2 emissions reduction to avoid the transfer of industries with high emissions.

Policy implications of this study can be summarized as follows: First, government should encourage export of new and high technological products with low CO_2 emissions, and curb export of traditional high-energy, high-pollution products. International trade has great significance in China's economic development, for exports account for a large proportion of the national output. However, a large proportion of China's CO_2 emissions are also the results of producing goods for export. China should strike a balance between economic development and CO_2 emissions reduction, through adjusting the foreign trade structure and increasing the proportion of high-tech exports with low CO_2 emissions. Second, CO_2 emissions embodied in interprovincial trade account for as much as 64.23% of China's total CO_2 emissions in 2002. The question that who has to be responsible for the CO_2 emissions embodied in interprovincial trade has a direct impact on the determination of regional CO_2 emissions reduction policies and targets. We suggest that China should adopt the "shared principle" (Lenzen et al., 2007). It means the responsibility should be shared between the interprovincial importer and exporter. Then provinces as interprovincial exporter are motivated to reduce CO_2 emissions through changing production technologies, and provinces as interprovincial importer are encouraged to reduce CO_2 emissions through moving in goods from provinces with low CO_2 emissions intensity. Third, western and central areas should selectively undertake the eastern industrial transfer to promote economic development and avoid the transfer of industries with high emissions. Strict environmental standards should be established for new enterprises. At the same time, the government should encourage the transfer of new and high technology industries, rather than just traditional industries.

Acknowledgments

The authors gratefully acknowledge the financial support from the Fundamental Research Funds for the Central Universities (Grant no.skzd11006) and the National Science Foundation of China (Grant no. 71173169). We also would like to thank the anonymous referees as well as the editors.

Appendix A

See Table A1.

Table A1
The abbreviated name of each province.

Abbreviation	Provinces	Abbreviation	Provinces
BJ	Beijing	HE	Henan
TJ	Tianjin	UB	Hubei
HB	Hebei	HU	Hunan
SX	Shanxi	GD	Guangdong
NM	Neimeng	GX	Guangxi
LN	Liaoning	HA	Hainan
JL	Jilin	CQ	Chongqing
HL	Heilongjiang	SC	Sichuan
SH	Shanghai	GZ	Guizhou
JS	Jiangsu	YN	Yunnan
ZJ	Zhejiang	SA	Shaanxi
AH	Anhui	GS	Gansu
FJ	Fujian	QH	Qinghai
JX	Jiangxi	NX	Ningxia
SD	Shandong	SJ	Xinjiang

Table B1
The abbreviated name of each sector.

Abbreviation	Sector
AG	Agriculture
CM	Coal mining and processing
CN	Crude petroleum and natural gas products
MO	Metal ore mining
NF	Non-ferrous mineral mining
MF	Manufacture of food products and tobacco processing
TG	Textile goods
WP	Wearing apparel, leather, furs, down and related products
SF	Sawmills and furniture
PP	Paper and products, printing and record medium reproduction
PC	Petroleum processing and coking
CH	Chemicals
NM	Nonmetal mineral products
MS	Metals smelting and pressing
MP	Metal products
ME	Machinery and equipment
TE	Transport equipment
EE	Electric equipment and machinery
ET	Electronic and telecommunication equipment
IM	Instruments, meters cultural and office machinery
OM	Other manufacturing products
EP	Electricity steam and hot water production and supply
GP	Gas production and supply
WS	Water production and supply
CO	Construction
TS	Transport, storage and post
WR	Wholesale, retail trade and hotel, restaurants
OT	Others

Appendix B

See Table B1.

References

Ackerman, F., Ishikawa, M., Suga, M., 2007. The carbon content of Japan–US trade. Energy Policy 35, 4455–4462.

Ahmad, N., Wyckoff, A., 2003. Carbon dioxide emissions embodied in international trade of goods. OECD STI Working Paper, p. 15.

Andrew, R., Peters, G.P., Lennox, J., 2009. Approximation and regional aggregation in multi-regional input–output analysis for national carbon footprint accounting. Economic Systems Research 21, 311–335.

Bastianoni, S., Pulselli, F.M., Tiezzi, E., 2004. The problem of assigning responsibility for greenhouse gas emissions. Ecological Economics 49, 253–257.

CESY, 2003. China Energy Statistical Yearbook, National Bureau of Statistics of China, National Development and Reform Commission. China Statistics Press, Beijing, China.

Davis, S.J., Caldeira, K., 2010. Consumption-based accounting of CO_2 emissions. In: Proceedings of the National Academy of Sciences, vol. 107, pp. 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.

Feng, K., Hubacek, K., Guan, D., 2009. Lifestyles, technology and CO_2 emissions in China: a regional comparative analysis. Ecological Economics 69, 145–154.

Guan, D., Hubacek, K., Weber, C.L., Peters, G.P., Reiner, D.M., 2008. The drivers of Chinese CO_2 emissions from 1980 to 2030. Global Environmental Change 18, 626–634.

Guan, D., Peters, G.P., Weber, C.L., Hubacek, K., 2009. Journey to world top emitter: an analysis of the driving forces of China's recent CO_2 emissions surge. Geophysical Research Letters 36, 1–5.

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.

Hertwich, E.G., Peters, G.P., 2009. Carbon footprint of nations: a global, trade-linked analysis. Environmental Science & Technology 43, 6414–6420.

Hertwich, E., Erlandsen, K., Sorenson, K., Aasness, J., Hubacek, K., 2002. Pollution embodied in Norway's import and export and its relevance for the environmental profile of households. Life-cycle approaches to sustainable consumption. IIASA Interim Report IR-02-073.

IEA, 2009. CO_2 emissions from fuel combustion 2009-highlights. Also available at: 〈http://www.iea.org/co2highlights/co2highlights.pdf〉.

IEA, 2010. CO_2 emissions from fuel combustion 2010-highlights. Also available at: 〈http://www.iea.org/publications/free_new_Desc.asp?PUBS_ID=2143〉.

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〉.

Kander, A., Lindmark, M., 2006. Foreign trade and declining pollution in Sweden: a decomposition analysis of long-term structural and technological effects. Energy Policy 34, 1590–1599.

Lenzen, M., 1998. Primary energy and greenhouse gases embodied in Australian final consumption: an input–output analysis. Energy Policy 26, 495–506.

Lenzen, M., Murray, J., Sack, F., Wiedmann, T., 2007. Shared producer and consumer responsibility—theory and practice. Ecological Economics 61, 27–42.

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

Lenzen, M., Wood, R., Wiedmann, T., 2010. Uncertainty analysis for Multi-Region Input–Output Models—a case study of the UK's carbon footprint. Economic Systems Research 22, 43–63.

Leontief, W., 1941. The Structure of American Economy, 1919–1929: An Empirical Application of Equilibrium Analysis. Harvard University Press, Cambridge.

Li, S.T., Qi, S.C., Xu, Z.Y., 2010. Chinese Regional Input–Output Table of 2002: Preparation and Application. The Science Publishing Company, Beijing.

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.

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

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.

Liu, X.B., 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.

Mäenpää, I., Siikavirta, H., 2007. Greenhouse gases embodied in the international trade and final consumption of Finland: an input–output analysis. Energy Policy 35, 128–143.

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

Minx, J.C., Wiedmann, T., Wood, R., Peters, G.P., Lenzen, M., Owen, A., Scott, K., Barrett, J., Hubacek, K., Baiocchi, G., Paul, A., Dawkins, E., Briggs, J., Guan, D., Suh, S., Ackerman, F., 2009. Input–output analysis and carbon footprinting: an overview of applications. Economic Systems Research 21, 187–216.

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

Munksgaard, J., Pade, L.L., Minx, J., Lenzen, M., 2005. Influence of trade on national CO_2 emissions. International Journal of Global Energy 23, 324–336.

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.

Peters, G.P., Minx, J.C., Weber, C.L., Edenhofer, O., 2011. Growth in emission transfers via international trade from 1990 to 2008. In: Proceedings of the National Academy of Sciences 108, pp. 8903–8908.

Peters, G.P., Weber, C.L., Guan, D., Hubacek, K., 2007. Chinas growing CO_2 emissions—a race between increasing consumption and efficiency gains. Environmental Science & Technology 41, 5939–5944.

Peters, G.P., 2007. Opportunities and challenges for environmental MRIO modeling: illustrations with the GTAP database. In: 16th International Input–Output Conference of the International Input–Output Association (IIOA), Istanbul, Turkey.

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

Peters, G.P., Hertwich, E.G., 2006a. Pollution embodied in trade: the Norwegian case. Global Environmental Change 16, 379–387.

Peters, G.P., Hertwich, E.G., 2006b. The importance of imports for household environmental impacts. Journal of Industrial Ecology 10, 89–109.

Peters, G.P., Herwich, E.G., 2008. CO_2 embodied in international trade with implications for global climate policy. Environmental Science and Technology 42, 1401–1407.

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.

Sánchez-Chóliz, J., Duarte, R., 2004. CO_2 emissions embodied in international trade: evidence for Spain. Energy Policy 32, 1999–2005.

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, 166–175.

Thomas, W., 2009. A review of recent multi-region input–output models used for consumption-based emission and resource accounting. Ecological Economics 69, 211–222.

Turner, K., Lenzen, M., Wiedmann, T., Barrett, J., 2007. Examining the global environmental impact of regional consumption activities—part 1: a technical note on combining input–output and ecological footprint analysis. Ecological Economics 62, pp. 37–44.

Wang, T., Watson, J., 2007. Who Owns China's Carbon Emissions?. Tyndall Centre for Climate Change Research Sussex, UK.

Weber, C.L., 2008. Uncertainties in constructing environmental multiregional input–output models. In: International Input–Output Meeting on Managing Environment in International Input–Output Association, Seville, Spain, pp. 1–31.

Weber, C.L., Matthews, H.S., 2007. Embodied environmental emissions in US international trade, 1997–2004. Environmental Science and Technology 41, 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, 301–316.

Wei, B.Y., Fang, X.Q., Wang, Y., 2009. Estimation of carbon emissions embodied in international trade for China: an input–output analysis. Journal of Beijing Normal University (Natural Science) 45, 413–419.

Wiedmann, T., 2009. A review of recent multi-region input–output models used for consumption-based emission and resource accounting. Ecological Economics 69, 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, 15–26.

Wiedmann, T., Wilting, H.C., Lenzen, M., Lutter, S., Palm, V., 2011. Quo Vadis MRIO? Methodological, data and institutional requirements for multi-region input–output analysis. Ecological Economics 70, 1937–1945.

Wiedmann, T., Wood, R., Minx, J., Lenzen, M., Guan, D., Harris, R., 2010. A carbon footprint time series of the UK—results from a multi-region input–output model. Economic Systems Research 22, 19–42.

Wilting, H., Vringer, K., 2007. Environmental accounting from a producer or a consumer principle: an empirical examination covering the world. In: 16th International Input–Output Conference, Istanbul, Turkey.

Wyckoff, A.W., Roop, J.M., 1994. The embodiment of carbon in imports of manufactured products: implications for international agreement on greenhouse gas emissions. Energy Policy 22, 187–194.

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, 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.

Zhang, M., Mu, H., Ning, Y., Song, Y., 2009. Decomposition of energy-related CO_2 emission over 1991–2006 in China. Ecological Economics 68, 2122–2128.

Zhang, X.P., 2009a. Carbon dioxide emissions embodied in China's foreign trade. Acta Geographica Sinica 12, 234–242.

Zhang, Y.G., 2009b. Structural decomposition analysis of sources of decarbonizing economic development in China: 1992–2006. Ecological Economics 68, 2399–2405.

Zhou, X., 2010. Emissions embodied in international trade and trade adjustment to national GHG inventory. Management Review 22, 17–24.