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The effects of direct trade within China on regional and national CO_2 emissions

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ABSTRACT

Curbing national carbon emissions and clarifying regional carbon reduction responsibility are two challenges faced by China, both of which are influenced by interregional trade. To exclude the influence of trade balance, this paper proposes a methodology to parcel the pollution haven hypothesis into a multi-regional input–output model, applies it to a longer time gap, which is made up of two representative periods of Chinese economy (1997–2002 and 2002–2007), and clarifies the provincial and sectoral contributions to national emissions. We find that (1) embodied CO_2 emissions first remain relatively stable and then increase sharply for the two periods, and the changing trends are mainly determined by the decreasing carbon intensity and the expanding trade scale, respectively. (2) With the secondary industry as the main contributor, regional carbon spillover is mainly concentrated in the coastal provinces but it contributes to an increase of CO_2 emissions in the central and western regions. (3) The coastal and inland provinces contribute to the increase of national carbon emissions through interregional imports and exports, respectively; but the pollution haven hypothesis is not obvious and is only observed in 2002.

1. Introduction

As the world's largest CO_2 emitter (IEA, 2009), China is a vast country with close interregional economic link and substantial variation in environmental regulations, which means that interprovincial trade may influence both regional and national CO_2 emissions (the pollution haven hypothesis, defined as a reduction in trade barriers will lead to a shifting of pollution-intensive industry from regions with stringent regulations to regions with weaker regulations (Copeland and Taylor, 2004)). This paper attempts to clarify the effects of interprovincial trade on China's regional and national CO_2 emissions in recent years, adopting a multi-regional input–output analysis mechanism.

Previous studies on CO_2 emissions embodied in China's international trade contain both static (e.g., Li and Hewitt, 2008) and dynamic (e.g., Pan et al., 2008; Zhang, 2009) analysis, while the existing studies on interregional trade are mainly limited to static analysis (e.g., Feng et al., 2013; Guo et al., 2012; Su and Ang, 2014), due to data availability (Feng et al, 2013). As far as we know, Meng et al.'s (2013) paper is the only dynamic analysis on China's interregional spillover of CO_2 emissions. However, Meng et al.'s study only analyzes the time span (2002–2007) when China's total CO_2 emissions increased quickly, and fails to present the period (1997–2002) when China's carbon intensity decreased sharply (Meng et al., 2011). The national CO_2 emissions and gross domestic production (GDP) of these two periods are shown in Fig. 1.

From 1997 to 2002, China experienced a quick economic growth, with annual average growth rate of 8.25%. However the total CO_2 emissions only increased from 3093 million tons of 1997–3377 million tons of 2002. In 1999, China even experienced a decrease in total CO_2 emissions. From 2002 to 2007, China's annual economic growth rate reached as high as more than 10%. At the same time, the total CO_2 emissions almost doubled during these 5 years. Not only the sharp increase in total CO_2 emission for the second period but also the quick decrease in carbon intensity for the first period attracts international concerns. For instance, some researchers even doubt the data accuracy of energy and emission statistics provided by the Chinese government (Liu and Yang, 2009; Peters et al., 2007; Sinton, 2001; Sinton and Fridley, 2000). This paper attempts to fill the gap that previous related studies only discuss the second period, and to provide a more comprehensive analysis on regional carbon spillover.

The pollution haven hypothesis is one of the most contentious areas of energy economics. For instance, Peters (2007), Zhang (2012), and Lopez

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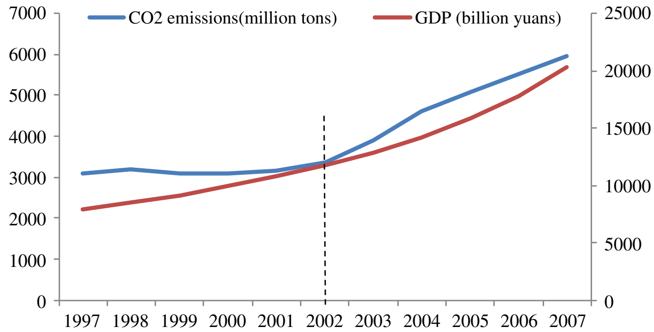

Fig. 1. National CO_2 emissions and GDP for 1997–2007. Note: National CO_2 emissions are obtained from the WIOD database (http://www.wiod.org/new_site/home.htm); national GDP data (the year 2000 is chosen as the base year) are obtained from China Statistical Yearbook of 2013 (http://www.stats.gov.cn/tjsj/ndsj/2013/indexch.htm).

et al. (2013) state that the total CO_2 emissions increase for trade, while Ackerman et al. (2007), Dietzenbacher and Mukhopadhyay (2007), and Tan et al.'s (2013) paper conclude that the pollution haven hypothesis does not hold. In addition, all these studies focus on the international trade, rather than interregional trade, although the latter has greater volume than the former. This paper attempts to discuss the pollution haven hypothesis from the perspective of trade within China and to clarify the effects of interregional trade on China's total CO_2 emissions. We hope to make some complements to previous studies (e.g. Feng et al., 2009; Zhang, 2009; Zhang et al., 2009), which analyze China's rapid increase in CO_2 emissions mainly from the angles of technology, economic structure, urbanization, and lifestyles.

Multi-regional input–output analysis (bi-regional input–output analysis can be observed as the simplest version of multi-regional input–output analysis with only two regions) can be divided into two types: one considers total bilateral trade between regions (EEBT approach) and the other considers trade to final consumption and endogenously determines trade to intermediate consumption (MRIO approach) (Peters, 2008). The EEBT approach has the transparency property and is considered superior when analyzing national trade and climate policy; the MRIO approach has the advantage of reflecting international feedback effects and is suitable for analyzing the global production system (Peters, 2008). Su and Ang (2010) further combine the EEBT and MRIO approaches and propose the hybrid emissions embodied in trade (HEET) approach. The characters of three approaches are summarized in Table 1.

There is a close relation among the three approaches. The EEBT and MRIO approaches are linked together through feedback effects (Su and Ang, 2011); and the HEET approach can be observed as a combination of the EEBT approach and the MRIO approach. Lopez et al. (2013) propose a methodology to parcel the pollution haven hypothesis into the bi-regional input–output analysis which adopts the MRIO approach to analyze the effects of regional specialization in value chain on total CO_2 emissions. However, this paper shows that the previous method fails to exclude the influence of trade balance on identifying the regional responsibility and tend to put more carbon reduction responsibility to the net exporter regions. This paper proposes a methodology to parcel the pollution haven hypothesis into the EEBT approach and we discuss the regional contribution and sectoral efficiency from the perspective of carbon intensity.

This paper chooses the EEBT approach according to the following reasons. First, this paper focuses on CO_2 emissions embodied in interregional trade within China, rather than the national trade. This means the HEET approach is not suitable for our research. Secondly, this paper analyzes the impacts of direct trade, rather than considering the interregional feedback effects. This means the MRIO approach is too complex for this study. Thirdly, in order to ensure comparability among different years, the main data (multi-regional input–output tables and interprovincial trade tables) of this paper are obtained from Development Research Center of the State Council, P.R.C. (Li et al., 2010; Xu and Li, 2008), which only supports the EEBT approach.

More specifically, based on China's multi-regional input–output tables of 1997, 2002 and 2007, this present paper calculates CO_2 emissions embodied in interprovincial trade from both regional and sectoral perspectives, discusses the interregional carbon spillover, and clarifies the effects of trade on provincial and national CO_2 emissions. The main results of this paper are shown as below.

1) This paper proposes a methodology to parcel the pollution haven hypothesis into the multi-regional input–output analysis, which excludes the influence of trade balance on identifying the regional responsibility. First, with a simple example, we show that previous calculation approach may attribute more responsibility to the net exporter regions for the pollution haven hypothesis. Secondly, the proposed approach shows that provinces with lower carbon intensities for imported goods or higher carbon intensities for exported goods, and sectors primarily located in regions with greater carbon intensity should be responsible for the pollution haven hypothesis. Thirdly, the proposed approach is applied to Chinese economy, to discuss the changing trends and main contributors of regional and national CO_2 emissions.
2) This paper extends previous studies on regional spillover of embodied CO_2 emissions within China to a longer time gap, including two representative periods of Chinese economy. First, China's CO_2 emissions embodied in interprovincial trade remain relatively stable for the first 5 years (from 2293.72 million tons in 1997 to 2390.71 million tons in 2002) and increase sharply for the second 5 years (6225.90 million tons in 2007). Secondly, the changing trends of the scale of embodied CO_2 emissions for the two periods (1997–2002 and 2002–2007) are mainly determined by the decreasing carbon intensity and the expanding trade scale, respectively. Thirdly, the provinces and sectors with a large scale of embodied CO_2 emissions mainly concentrate in the coastal region and the secondary industry, respectively, and the most obvious carbon spillover is from the Pearl and Yangtze River Delta regions to the provinces around the Bohai Sea region.
3) This paper clarifies the effects of interregional trade on national CO_2 emissions from the perspectives of provincial and sectoral contributions. First, the pollution haven hypothesis was only held in 2002, and the interregional trade contributed to changes of national carbon emission by −2010.01, 38.91 and −118.49 million tons respectively for 1997, 2002 and 2007, respectively. Secondly, the coastal and inland provinces contribute to national CO_2 emissions through interregional imports and exports, respectively; and the

Table 1
Characters of three approaches of multi-regional input–output analysis.

	EEBT	MRIO	HEET
Features	Considering direct trade	Considering indirect trade	Considering direct and indirect trade
Advantages	Transparency	Entirely reflecting the interregional feedback effects	Partly reflecting the interregional feedback effects
Applications	Carbon emissions embodied in regional direct trade	Impacts of regional production system on regional carbon leakage	Impacts of regional production system on regional carbon leakage
Examples	Guo et al. (2012)	Lopez et al. (2013)	Su and Ang (2010, 2014)

electricity generation sector plays an important role in the pollution haven hypothesis. Thirdly, the sharp decrease in carbon intensity for 1997–2002 is mainly resulted from technology improvement, rather than interregional industrial restructuring; but in the second period (2002–2007), the condition that coastal provinces mainly transfer energy intensive firms to inland provinces changes gradually.

The rest of the paper is organized as follows. Section 2 introduces the calculation method and data preparation. Section 3 presents the calculation results. Section 4 provides further discussion on the final results, followed by conclusions and policy implications in Section 5.

2. Methodology and data

Input–output analysis (Leontief, 1941), widely used for calculating embodied CO_2 emissions and evaluating the pollution haven hypothesis (Turner et al., 2007; Wiedmann, 2009; Wiedmann et al., 2007, 2011), can be divided into two main types: single-regional input–output analysis (e.g. Gavrilova and Vilu, 2012; Lenzen, 1998) and multi-regional input–output analysis (e.g. Bordigoni et al., 2012; Wiedmann et al., 2010). Compared with the former, multi-regional input–output analysis reflects not only the relationship among different sectors, but also the economic links among different regions. Specifically, this present paper adopts the EEBT approach, which has the transparency property and is considered superior when analyzing national trade and climate policy (Peters, 2008).

Previous studies on embodied emissions apply competitive or non-competitive imports assumptions. The main difference on these two approaches is that the former adopts the same technology assumption of different regions. Since this paper focuses on CO_2 emissions embodied in trade within China and the difference on technology among regions within a country is relatively smaller than that among different countries, we adopt the competitive assumption. However, it should be pointed out that the same technology assumption results in a larger estimation on embodied emissions and the results can only be treated as an approximate value (Su and Ang, 2013; Su et al., 2013).

2.1. Calculation methodology

The standard input–output analysis framework begins with an accounting balance of monetary flows (United Nations, 1999).

$$x_i^r = a_{i1}^r x_1^r + a_{i2}^r x_2^r + \cdots + a_{in}^r x_n^r + y_i^r + ex_i^r - im_i^r \quad (1)$$

where x_i^r is the output of province r in sector i, a_{ij}^r is the direct consumption coefficient of province r, y_i^r is the domestic final consumption of province r in sector i, ex_i^r and im_i^r are the interregional and international imports and exports of province r in sector i. 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, EX^r be the vector of coefficients ex_i^r, IM^r be the vector of coefficients im_i^r, then the expression for the balance becomes:

$$X^r = A^r X^r + Y^r + EX^r - IM^r. \quad (2)$$

To solve for X^r, we get

$$X^r = (1 - A^r)^{-1}(Y^r + EX^r - IM^r) \quad (3)$$

where $(1 - A^r)^{-1}$ is known as the Leontief inverse matrix which shows the total production required to satisfy one unit of final demand in the economy. Given the direct CO_2 emissions coefficient in each sector f_i^r, then the CO_2 emissions of province r in sector i can be expressed as:

$$c_i^r = f_i^r x_i^r \quad (4)$$

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

$$c^r = F^r (1 - A^r)^{-1}(Y^r + EX^r - IM^r) \quad (5)$$

where $F^r(1 - A^r)^{-1}$ is the embodied CO_2 emissions coefficient. Here we only consider total bilateral trade between regions (EEBT) without splitting trade flow into components of intermediate and final consumption (Peters, 2008). The CO_2 emissions embodied in trade between province r and province s can be expressed as:

$$ct^{rs} = F^r (1 - A^r)^{-1} T^{rs} \quad (6)$$

where ct^{rs} is the transfer of embodied CO_2 emissions between province r and province s; T^{rs} is the bilateral trade matrix between province s and province r. Then the CO_2 emissions embodied in interprovincial imports and exports of province r can be expressed as follows:

$$cm^r = \sum_s ct^{sr} \quad (7)$$

$$ce^r = \sum_s ct^{rs} \quad (8)$$

where cm^r is the CO_2 emissions embodied in the interprovincial imports of province r; ce^r is the CO_2 emissions embodied in the interprovincial exports of province r. The relationship between provincial CO_2 emissions under different principles is shown as follows:

$$c_c^r = c_p^r + cm^r - ce^r \quad (9)$$

where c_c^r is the CO_2 emission of province r under the consumption accounting principle; c_p^r is the CO_2 emission of province r under the production accounting principle.

With carbon spillover, regional CO_2 emissions are influenced by interregional trade. The methodology of emission balance, the production based emissions minus the consumption based emissions, shows how this effect differs among different regions (Chen and Chen, 2011; Lopez et al., 2013). According to Eq. (9), the emission balance of each province is shown as follows:

$$EB^r = c_p^r - c_c^r = ce^r - cm^r. \quad (10)$$

If the sign of EB^r is negative, it means the corresponding province reduce its direct CO_2 emissions through interprovincial trade. And, the positive sign means that interprovincial trade increases the direct CO_2 emissions of the corresponding province, which bears carbon reduction responsibility of other provinces. Nevertheless, it is impossible to use CO_2 emissions embodied in imports and exports to know the influence of interregional trade on national CO_2 emissions because the aggregation of trade and emission balances for all regions is always zero (Lopez et al., 2013).

Similar with previous studies (Chen and Chen, 2011; Dietzenbacher and Mukhopadhyay, 2007; Lopez et al., 2013; Zhang, 2012), we use the difference between emissions linked to exports (*EEX*) and emissions avoided by imports (*EAM*, some studies use the *EAM* to estimate the emissions embodied in imports, while this paper can calculate embodied emissions accurately and only uses *EAM* to evaluate the pollution haven hypothesis) to evaluate whether international trade increases or decreases the total emissions, which is called the balance of avoided emissions (*BAE*). The positive sign of *BAE* confirms the existence of pollution haven hypothesis, which means that CO_2 emissions generated by interprovincial trade are higher than those that had been produced within the country using domestic technology. The mathematical expression is:

$$BAE^{1-n} = EEX - EAM = \sum_n \left(\varepsilon^n EX^n - \varepsilon^n IM^n\right) \tag{11}$$

where X^r and M^r are interprovincial exports and imports vectors of region r. ε^r is the domestic emissions multiplier for region r, which is calculated by multiplying the direct emissions coefficient for region r by the Leontief inverse ($\varepsilon^r = F^r(1 - A^r)^{-1}$). The interprovincial trades satisfy $EX^r = \sum_s T^{rs}$ and $IM^r = \sum_s T^{sr}$. Then, we obtain

$$\begin{aligned} BAE_M^{1-n} &= EEX - EAM = \left(\varepsilon^1 \sum_s T^{1s} + \varepsilon^2 \sum_s T^{2s} + \ldots + \varepsilon^n \sum_s T^{ns}\right) \\ &\quad - \left(\varepsilon^1 IM^1 + \varepsilon^2 IM^2 + \ldots + \varepsilon^n IM^n\right) = \sum_n \underbrace{\left(\sum_s \varepsilon^s T^{sr} - \varepsilon^r IM^r\right)}_{BAE^{1.r}}. \end{aligned} \tag{12}$$

From the equation $IM^r = \sum_s T^{sr}$, we can see that the sign of the sub-balance for province r is only determined by provincial carbon intensities. A positive sign of sub-balance for province r ($BAE^{1.r}$) means that province r has a relatively low carbon intensity for the imported products, and it contributes to an increase of national CO_2 emissions. Similarly, a negative sign means that province r imports products from regions with lower carbon intensities, resulting in a decrease in total CO_2 emissions.

$$\begin{aligned} BAE_X^{1-n} &= EEX - EAM = \left(\varepsilon^1 EX^1 + \varepsilon^2 EX^2 + \ldots + \varepsilon^n EX^n\right) \\ &\quad - \left(\varepsilon^1 \sum_s T^{s1} + \varepsilon^2 \sum_s T^{s2} + \ldots + \varepsilon^n \sum_s T^{sn}\right) \\ &= \sum_n \underbrace{\left(\varepsilon^r EX^r - \sum_s \varepsilon^s T^{rs}\right)}_{BAE^{2.r}}. \end{aligned} \tag{13}$$

From the equation $EX^r = \sum_s T^{rs}$, we can see that the sign of the sub-balance for province r is also only determined by provincial carbon intensities. A positive sign of sub-balance for province r ($BAE^{2.r}$) means that province r has a relatively high carbon intensity for the exported products, and it increases national CO_2 emission. While a negative sign means that provinces export products with relatively lower carbon intensities and contribute to the reduction of total CO_2 emissions. Although Eqs. (12) and (13) analyze the regional responsibility from the perspective of interprovincial imports and exports respectively, the final conclusion is consistent ($BAE_X^{1-n} = BAE_M^{1-n}$). In addition, Eqs. (12) and (13) only present the regional responsibility from the perspective of interprovincial imports and exports respectively. Here we present the combination effect:

$$\begin{aligned} BAE^{1-n} &= BAE_M^{1-n} = BAE_X^{1-n} = \left(BAE_M^{1-n} + BAE_X^{1-n}\right)/2 \\ &= \sum_n \underbrace{\left(\varepsilon^r EX^r - \sum_s \varepsilon^s T^{rs} + \sum_s \varepsilon^s T^{sr} - \varepsilon^r IM^r\right)/2}_{BAE^{3.r}}. \end{aligned} \tag{14}$$

$BAE^{3.r}$ reflects both the import and export perspectives, which presents the provincial contribution for national CO_2 emissions. If the sign is positive, this means that the province contributes to the total CO_2 emissions, through interregional trade. To reflect the sectoral efficiency, we further adjust Eqs. (12) and (13) and get:

$$BAE_M^{1-n} = \sum_i \underbrace{\sum_r \left(\sum_s \varepsilon_i^s t_i^{sr} - \varepsilon_i^r im_i^r\right)}_{BAE^{4.i}} \tag{15}$$

$$BAE_X^{1-n} = \sum_i \underbrace{\sum_r \left(\varepsilon_i^r ex_i^r - \sum_s \varepsilon_i^s t_i^{rs}\right)}_{BAE^{5.i}} \tag{16}$$

where $BAE^{4.i}$ and $BAE^{5.i}$ are the sectoral sub-balances of sector i from the perspectives of imports and exports. A positive sign means that firms of this sector are mainly located in the region with greater carbon intensity, and the spatial distribution of this sector is inefficient. For $\sum_r \sum_s \varepsilon_i^s t_i^{sr} = \sum_r \varepsilon_i^r ex_i^r$ and $\sum_r \varepsilon_i^r im_i^r = \sum_r \sum_s \varepsilon_i^s t_i^{rs}$, we can obtain $BAE^{4.i} = BAE^{5.i}$. This means that it is consistent to analyze the sectoral efficiency from either import or export perspectives.

2.2. Comparison with previous approach

To clarify the regional and sectoral contributions to the total CO_2 emissions, this paper parcels the pollution haven hypothesis into the multi-regional input–output analysis that adopts the EEBT approach. This section compares the calculation approach proposed by this paper with that of the previous studies through an intuitive example.

We suppose that there are two regions, region 1 and region 2. Each region contains one sector, with sectoral carbon intensity represented by ε^1 and ε^2,[1] respectively. Without loss of generality, we assume that $\varepsilon^1 > \varepsilon^2$. For simplicity, we assume that the trade flow is only from region 1 to region 2, which is represented by t_{12}. In other words, export from region 1 and import of region 2 are the same as the trade flow volume, $ex^1 = im^2 = t_{12}$ and $ex^2 = im^1 = 0$.

According to the previous analytic framework, the expression proposed to evaluate the pollution haven hypothesis is shown as follows:

$$\begin{aligned} BAE^{1\text{-}2} &= EEX - EAM = \left(\varepsilon^1 ex^1 + \varepsilon^2 ex^2\right) - \left(\varepsilon^1 im^1 + \varepsilon^2 im^2\right) \\ &= \left(\varepsilon^1 ex^1 - \varepsilon^1 im^1\right) + \left(\varepsilon^2 ex^2 - \varepsilon^2 im^2\right). \end{aligned} \tag{17}$$

As mentioned above, the sign of BAE^{1-2} reflects the effects of interregional trade on total carbon emission, and the sign of the two sub-balances of avoided emissions for region 1 ($\varepsilon^1 ex^1 - \varepsilon^1 im^1$) and region 2 ($\varepsilon^2 ex^2 - \varepsilon^2 im^2$) can be used to identify the country responsible (Lopez et al., 2013). For $\varepsilon^1 > \varepsilon^2$, we obtain $BAE^{1-2} = t_{12}(\varepsilon^1 - \varepsilon^2) > 0$. This means interregional trade between two regions contributes to an increase in the total CO_2 emissions, and the pollution haven hypothesis holds. Region 2 has an absolute environmental advantage in producing exchanged products, while interregional trade results that tradable products are produced in region 1 with higher carbon intensity. Therefore, interregional trade will result in greater total CO_2 emissions, and the import behavior of region 2 contributes to the increase of total CO_2 emissions. If region 2 obtains import products from the domestic market, there will be a smaller level of total emissions. However, the conclusion of the previous analytic framework is that region 1 is responsible for the increase of total CO_2 emissions, and region 2 contributes to a decrease of total CO_2 emissions, for $\varepsilon^1 ex^1 - \varepsilon^1 im^1 = \varepsilon^1 t_{12} > 0$ and $\varepsilon^2 ex^2 - \varepsilon^2 im^2 = -\varepsilon^2 t_{12} < 0$. This means that the previous analytical framework provides a counter-intuitive conclusion.

[1] Different from the input-output analysis, ε_1 and ε_2 are not vectors, but two parameters, because of the one sector assumption.

Table 2
Carbon emission balance under different perspectives.

	$BAE^{1.r}$	$BAE^{2.r}$	$BAE^{3.r}$
Region 1	0	$(\varepsilon^1 - \varepsilon^2)t_{12}$	$(\varepsilon^1 - \varepsilon^2)t_{12}/2$
Region 2	$(\varepsilon^1 - \varepsilon^2)t_{12}$	0	$(\varepsilon^1 - \varepsilon^2)t_{12}/2$
Total	$(\varepsilon^1 - \varepsilon^2)t_{12}$	$(\varepsilon^1 - \varepsilon^2)t_{12}$	$(\varepsilon^1 - \varepsilon^2)t_{12}$

To address the problem that the previous calculation framework fails to present the provincial contribution to total CO_2 emissions, this paper proposes a modified calculation approach and discusses from the import, export, and comprehensive perspectives. The calculation results, according to Eqs. (12), (13) and (14), are summarized in Table 2.

Table 2 shows that, from different perspectives, the balance of avoided emissions shares the same result $(\varepsilon^1 - \varepsilon^2)t_{12}$. It is also consistent with the previous analytic mechanism, meaning that the two mechanisms share the same results on the environmental effects of the interregional trade. However, the sub-balance provides more information than the previous analytical framework. From the perspective of import, the sub-balance for regions 1 and 2 are 0 and $(\varepsilon^1 - \varepsilon^2)t_{12}$. This means that region 1 has no influence on total CO_2 emissions, because there is no import for region 1. At the same time, region 2 contributes to an increase in total CO_2 emissions ($(\varepsilon^1 - \varepsilon^2)t_{12} > 0$), because it imports products from region with higher carbon intensities, rather than obtaining them from the domestic market. From the perspective of export, the sub-balance for regions 1 and 2 are $(\varepsilon^1 - \varepsilon^2)t_{12}$ and 0, respectively. This means that only the exports of region 1 should be responsible for the increase of CO_2 emissions. From a comprehensive perspective, the sub-balance for the two regions are both $(\varepsilon^1 - \varepsilon^2)t_{12}/2$, meaning that both region 1 and region 2 should be responsible for the pollution haven hypothesis.

The comparison between the two analytic frameworks shows that they share the same result on the pollution haven hypothesis, but the modified framework provides more reasonable information on regional responsibility. The differences between these two methods can be explained from their different analytical perspectives. The previous analytical framework explains the regional responsibility from the perspective of trade structure, so only the regions that are net exporters should be responsible for the pollution haven hypothesis. However, the modified analytic framework explains it from the perspective of sectoral carbon intensity.

2.3. Data collection

This study requires three datasets: input–output tables, interprovincial trade tables and the corresponding CO_2 emissions data of each sector. We employed China's time-series multi-regional input–output tables (MRIOT) from the Development Research Center of the State Council, P.R.C. (Li et al., 2010; Xu and Li, 2008), for 1997, 2002, and 2007. First, the consistency of data sources ensures comparability among different years. Secondly, the 3 years respectively represent the three stages of China's CO_2 emissions in recent years (Meng et al., 2011). Thirdly, the time-series MRIOT provides the necessary information for our calculation, such as the sectoral data on China's interprovincial trade (interprovincial trade tables). Each sector's direct CO_2 emissions coefficient is calculated as CO_2 emissions per unit of output, which is obtained using the energy statistics and the method provided in IPCC (2006).

This study calculates the CO_2 emissions, based on the final energy consumption data from the energy balance table of each province (CESY, 1998, 2003, 2008), including major energy varieties. First, under the assumption that all the carbons in the fuel are completely combusted and transferred into the carbon dioxide form, we calculate the CO_2 emissions of each kind of energy by multiplying the relative emission factors (IPCC, 2006). Secondly, we obtain the total CO_2 emissions of each province by adding together the emission of each energy variety. Thirdly, by summing all the provinces' emission data, we can get the total emission of China.[2]

We have to choose a consistent sectoral level for different datasets. The provincial input–output tables have as much as 42 sectors, but the energy balance tables have only six sectors. Su et al. (2010) and others suggest how to aggregate the input–output tables and disaggregate the energy balance tables to match each other. However, for this paper, the main constraint of the sectoral level choice is the interprovincial trade tables of 2007 (12 sectors, shown in Appendix A); therefore, we aggregate the input–output table and disaggregate the energy balance table to match the interprovincial trade table of 2007. In addition, this paper estimates the sectoral carbon intensity of some provinces, without statistics on sectoral energy consumption, according to that of neighboring year or provinces. For other provinces with statistics on the major energy consumption of each sector, the sectoral CO_2 emissions intensities are calculated directly.

In this paper, 30 provinces are analyzed, the abbreviated names of which are shown in Appendix B. Tibet, Hong Kong, Macau, and Taiwan are not analyzed because of data acquisition problems. In order to facilitate reporting and discussion of our results, 30 provinces are further geographically divided into eight regions (shown in Fig. 2): the northeastern region (NE), made up of Jilin, Liaoning and Heilongjiang; the northern coastal region (NC), made up of Beijing, Tianjin, Hebei and Shandong; the eastern coastal region (EC), made up of Shanghai, Jiangsu and Zhejiang; the southern coastal region (SC), made up of Fujian, Guangdong and Hainan; the region of the middle reaches of Yellow River (YER), made up of Shaanxi, Shanxi, Henan and Inner-Mongolia; the region of the middle reaches of the Yangtze River (YAR), made up of Hubei, Hunan, Jiangxi and Anhui; the southwestern region (SW), made up of Yunnan, Guizhou, Sichuan, Chongqing and Guangxi; the northwestern region (NW), made up of Gansu, Qinghai, Ningxia and Xinjiang.

3. Results

Based on the methodology and data presented above, we calculate the CO_2 emissions embodied in interprovincial trade and discuss the effects of trade on provincial and national CO_2 emissions.

3.1. Preliminary analysis

CO_2 emissions embodied in trade within China present a trend that is relatively stable for the first 5 years (1997–2002) and sharply increases for the second 5 years (2002–2007). The stable trend from 1997 (2293.72 million tons) to 2002 (2390.71 million tons) can be explained from two perspectives: economic scale and carbon intensity. Influenced by the Asian financial crisis, China's economy was in the process of a soft landing, and the interprovincial trade volume had increased slowly during this period. In addition, China's carbon intensity obviously decreased for this period. For instance, the emission intensity in 2000 decreased by 20.45%, compared with 1997 (Meng et al., 2011). As the influence of the Asian financial crisis faded away, China's economy recovered gradually and entered a stage of rapid development. For instance, the annual growth rate in GDP of each year was higher than 10% for the second period. Simultaneously, CO_2 emissions embodied in interprovincial trade increased quickly, which reached as much as 6225.90 million tons in 2007. In this section, we further analyze the calculation results from both provincial and sectoral perspectives.

[2] It should be pointed out that the sum of regional emissions is greater than the national emissions, caused by the statistical differences in national and regional energy consumption (Guan et al., 2012).

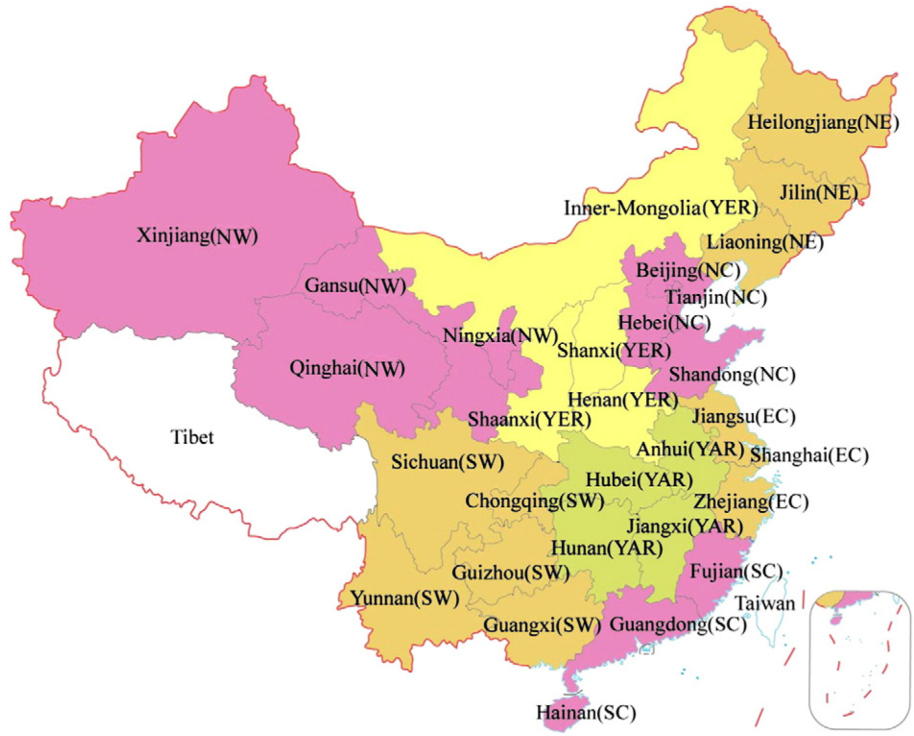

Fig. 2. Map of China's provinces.

3.1.1. Provincial embodied CO_2 emissions

According to Eq. (5), CO_2 emissions embodied in interprovincial imports and exports for each province are presented in Tables 3 and 4. The abbreviated name of each province is provided in Appendix B.

Table 3 shows that most provinces experience a sharp increase in CO_2 emissions embodied in interprovincial imports for the second 5 years (2002–2007). For the first 5 years, however, some provinces, such as Jiangsu, even experience a sharp decrease in it. Because of the impact of the Asian financial crisis, the interprovincial import of Jiangsu decreased from 59.16 million yuan in 1997 to 36.94 million yuan in 2002, so the imported CO_2 emissions decrease at the same time. With the fade away of the influence of the Asian financial crisis, the embodied CO_2 emissions of most provinces increase sharply. For instance, it increases nearly four times for Henan and Guangdong.

Table 3 also shows that provinces with large volumes of embodied CO_2 emissions are mainly located in the coastal provinces, such as Guangdong, Zhejiang, and Hebei. The central and western provinces have relatively lower levels of embodied CO_2 emissions. China's reform and opening up contributes to not only the quick economic development but also the huge regional gap. The coastal provinces have become the most active, rapid-developing and strongly competitive regions by superiorities in location and policies. The coastal region has the largest demand market, which determines the large volume of embodied CO_2 emissions. In addition, this paper does not distinguish the international trade from each province's final demand. Therefore, the fact that the coastal region is China's largest export base also contributes to the large volume of embodied CO_2 emissions, such as in Guangdong.

Table 4 shows that CO_2 emissions embodied in interprovincial exports share the same changing trend with that of imports. However, the central and western provinces take a relatively larger proportion of the CO_2 emissions embodied in interprovincial exports than that of imports, which can be explained from the perspectives of economic structure and carbon intensity. First, most central and western provinces, such as Shanxi, Shaanxi, and Inner-Mongolia, constitute China's energy base, which provides the necessary energy resources to support the quick economic development of the coastal regions, so energy-intensive industries hold a large proportion of the interprovincial

Table 3
CO_2 emissions embodied in interprovincial imports of 30 provinces (million tons CO_2).

Province	Region	1997	2002	2007	Province	Region	1997	2002	2007
JL	NE	51.31	107.50	244.81	HE	YER	87.29	76.19	296.39
LN	NE	60.39	81.50	244.41	NM	YER	35.87	29.50	113.99
HL	NE	74.78	62.71	138.11	UB	YAR	70.14	55.18	88.23
BJ	NC	53.86	163.17	273.59	HU	YAR	68.45	57.68	151.75
TJ	NC	72.38	77.22	228.26	JX	YAR	38.91	44.94	107.53
HB	NC	171.79	178.91	563.29	AH	YAR	116.76	107.18	266.12
SD	NC	125.30	155.09	256.99	YN	SW	39.74	36.73	106.08
SH	EC	127.61	98.39	309.89	GZ	SW	38.34	23.60	77.09
JS	EC	261.92	152.86	463.10	SC	SW	54.01	48.00	112.70
ZJ	EC	103.65	238.88	595.18	CQ	SW	56.99	90.75	110.50
FJ	SC	52.15	48.67	152.42	GX	SW	59.18	60.07	116.78
GD	SC	256.22	195.37	732.15	GS	NW	36.38	30.75	57.65
HA	SC	20.07	19.85	8.32	QH	NW	13.99	13.10	10.88
SA	YER	48.52	65.10	228.31	NX	NW	10.05	16.29	28.01
SX	YER	43.72	23.43	65.14	SJ	NW	43.93	32.11	78.23

Table 4
CO_2 emissions embodied in interprovincial exports of 30 provinces (million tons CO_2).

Province	Region	1997	2002	2007	Province	Region	1997	2002	2007
JL	NE	93.59	164.04	284.11	HE	YER	88.59	97.85	389.46
LN	NE	111.38	147.06	323.73	NM	YER	93.75	104.91	346.82
HL	NE	78.65	55.97	172.32	UB	YAR	70.62	69.91	143.59
BJ	NC	38.97	68.91	113.76	HU	YAR	50.33	47.79	185.58
TJ	NC	74.33	76.18	193.95	JX	YAR	33.00	33.86	51.82
HB	NC	229.86	286.38	816.67	AH	YAR	209.63	141.75	300.52
SD	NC	111.22	82.88	462.37	YN	SW	29.56	25.90	146.31
SH	EC	97.75	99.13	195.43	GZ	SW	45.33	55.22	171.33
JS	EC	185.35	93.85	376.14	SC	SW	48.26	36.64	69.40
ZJ	EC	60.59	119.49	300.66	CQ	SW	78.65	119.03	95.20
FJ	SC	19.04	18.98	76.96	GX	SW	36.43	46.60	81.77
GD	SC	115.79	116.24	272.70	GS	NW	42.74	41.07	82.64
HA	SC	6.14	9.87	9.67	QH	NW	9.66	8.50	2.90
SA	YER	47.41	55.97	237.62	NX	NW	13.20	35.56	65.36
SX	YER	110.22	91.64	180.57	SJ	NW	63.68	39.56	76.54

exports of these provinces. Secondly, the central and western provinces have higher carbon intensity than the coastal provinces (Meng et al., 2011), the latter has relatively stricter environmental protection laws and regulations, more advanced emission-cutting technologies and more developed modern service industries.

Consistent with the conclusion of previous studies (Feng et al., 2013; Guo et al., 2012), Hebei is the province with the highest CO_2 emissions embodied in exports. Surrounded by Hebei, Beijing and Tianjin have strong economic links with Hebei, and large amounts of goods are moved from Hebei to Beijing and Tianjin, especially goods from high

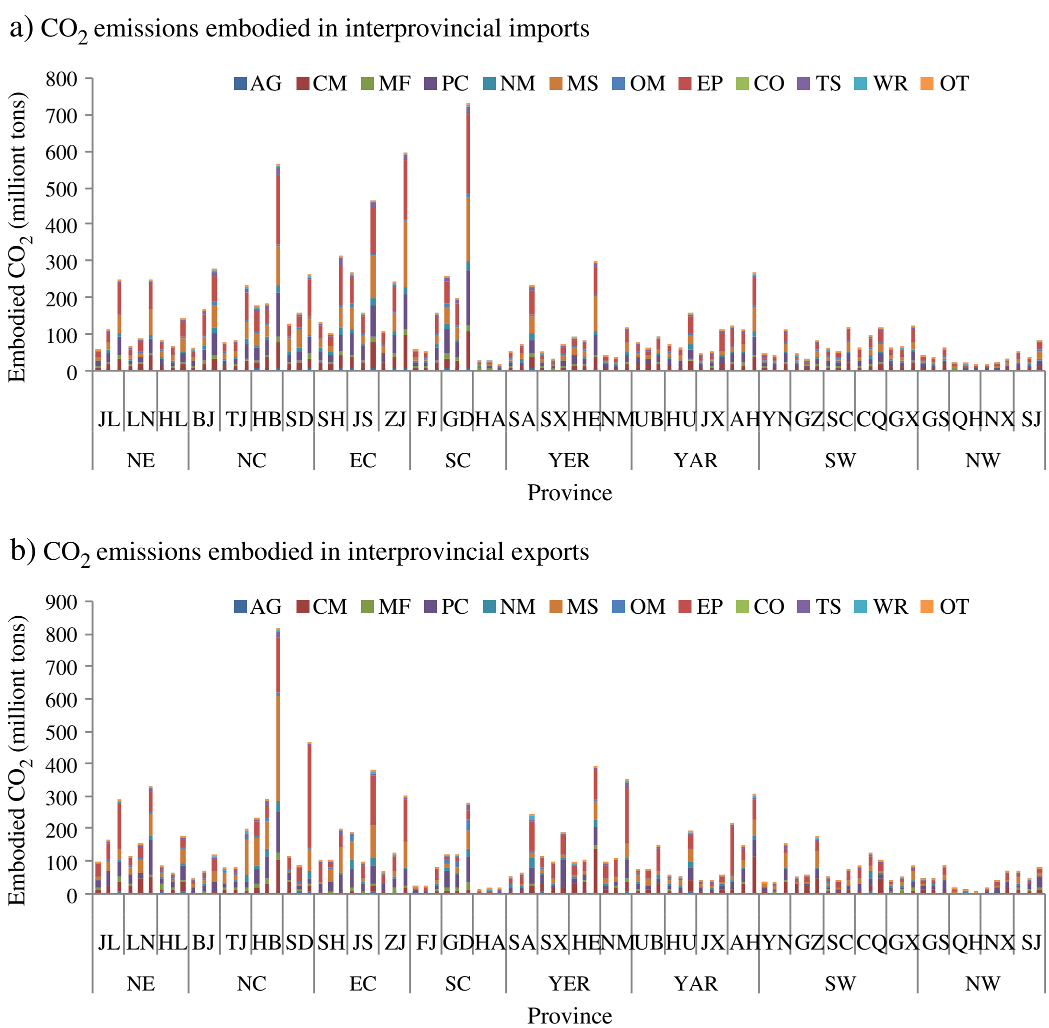

Fig. 3. CO_2 emissions embodied in interprovincial trade for each sectors. Notes: we present the information of 3 years (1997, 2002, and 2007) for each province, which is not clarified due to the limited space. The three bars of each province are corresponding to 1997, 2002 and 2007, from left to right. This is the same for Fig. 4.

Table 5
CO_2 emissions embodied in interprovincial trade of 12 sectors (million tons CO_2).

	AG	CM	MF	PC	NM	MS	OM	EP	CO	TS	WR	OT	Total
1997	39.37	263.68	109.51	527.40	126.90	431.19	84.62	593.98	0.97	75.86	21.55	18.69	2293.72
2002	30.72	306.35	116.03	510.05	126.13	461.59	59.70	629.11	1.99	103.96	22.78	22.30	2390.71
2007	53.89	836.52	176.09	1188.85	292.99	1427.00	102.76	1854.14	5.29	207.11	49.49	31.78	6225.90

energy consumption and high emissions sectors, so the embodied CO_2 emissions of Hebei are much higher than that of other provinces.

3.1.2. Sectoral embodied CO_2 emissions

The above presents the geographical characteristics of China's embodied CO_2 emissions; then we analyze it from the sectoral perspective. For the 3 years, the CO_2 emissions embodied in the interprovincial imports and exports of each province's 12 sectors (the abbreviated name of each sector is provided in Appendix A) are shown in Fig. 3.

Fig. 3 shows that for most provinces, the sectors with large interprovincial embodied CO_2 emissions belong to the secondary industry. It reflects the fact that industrial products account for a large proportion in China's interprovincial trade and the CO_2 emissions intensity of the secondary industry is higher than those of the primary and tertiary industries. For instance, the sector with the largest embodied CO_2 emissions is the sector EP (electricity steam, gas and water production and supply), followed by the sector MS (metals smelting and pressing, and metal products) and the sector PC (petroleum processing, coking and chemicals). In 2007, the embodied CO_2 emissions of three sectors reach as much as 1854.14, 1427.00, and 1188.85 million tons respectively. The total CO_2 emissions embodied in each sector is shown in Table 5. It should be noted that the total sectoral emissions embodied in interprovincial imports is equal to those of exports, so we do not differentiate between the sectoral CO_2 emissions embodied in interprovincial imports and exports.

Different from the international trade, electricity transfer is popular among regions within one country. As China's main energy, coal takes up a large proportion in the energy consumption structure. However, the coal resources are concentrated in the central and western provinces, while the consumptions are concentrated in the eastern developed provinces. The geographical inverse distribution of production and consumption results in large-scale, long-distance energy transportation among provinces. With the interconnection process of the regional power grid and the construction of high voltage and extra high voltage transmission lines, electricity becomes the dominant form of energy transfer among provinces. So the sector EP corresponds to the largest embodied CO_2 emissions.

3.2. Regional perspective

From 1997 to 2007, the regional CO_2 emissions have two principle characteristics. First, there is a decreasing trend in the absolute volume of CO_2 emissions from coastal and central to western regions, which is consistent with the economic development degree. Secondly, there is an increasing trend in the growth rate of CO_2 emissions from coastal and central to western regions. Meng et al. (2011) explain it from the perspective of the “Eleventh Five Year Plan” for national economic and social development. This paper discusses the changing of regional CO_2 emissions from the perspective of interprovincial trade, to clarify the effects of trade on regional CO_2 emissions.

3.2.1. Regional spillover of embodied CO_2 emissions

The above part presents the gross embodied CO_2 emissions of each province and this part further discusses regional carbon spillover, which reflects the source and direction of interregional CO_2 emission transfer. Because the transfer matrix of 30 provinces is too complex, here we only present the emission spillovers of eight regions. According to Eq. (6), the interregional transfer of embodied CO_2 emissions is shown in Table 6.

In 1997, the largest scale of regional CO_2 emission transfer is *YAR* → *EC*, and the two main directions of the CO_2 emission transfer are within the coastal regions and from the central region to the coastal region. It should be noted that the diagonal element in the matrix is the CO_2 emission transfer in the provinces located in the same region. The coastal region is the most active region in China, so the interprovincial trade volume is also large enough. Closely connect to the coastal regions, the regions of middle reaches of the Yellow River and Yangtze River provide the necessary resources for production in the coastal regions, so it also contributes to the regional CO_2 emission transfer.

In 2002, the largest scale of regional CO_2 emission transfer is within the northern coastal region, which is consistent with the previous conclusion that there is a large scale of CO_2 emissions transferred from Hebei to Beijing and Tianjin. In addition, the top 5 CO_2 emission transfers show that most embodied CO_2 emissions are mainly transferred to the northern and eastern coastal regions. It further presents the important role of coastal region in regional carbon spillover.

In 2007, the embodied CO_2 emissions transferred to the northern and eastern coastal regions also take up as much as 21.98% and 21.24% of the total emission transfer. Moreover, the embodied CO_2 emissions from northern coastal region and the region of middle reaches of the Yellow Rriver take up as much as 25.49% and 18.54% of the total emission transfer. This means the embodied CO_2 emission transfer gradually concentrates on the coastal and surrounding regions, while the western region contributes relatively little to the regional CO_2 emission transfer.

Table 6
The regional spillover of embodied CO_2 emissions (million tons CO_2).

	NE	NC	EC	SC	YER	YAR	SW	NW
a) The regional spillover of embodied CO_2 emissions for 1997								
NE	44.06	55.32	49.15	30.17	26.55	37.72	29.06	11.6
NC	33.75	85.39	91.35	71.64	49.73	56.78	45.22	20.5
EC	19.04	64.78	56.54	78.36	30.7	46.14	33.21	14.93
SC	12.84	20.97	41.6	7.67	15.1	18.66	18.42	5.7
YER	26.11	68.35	82.91	33.56	25.49	51.62	34.8	17.13
YAR	24.95	63.71	96.55	59.09	33.83	34.1	35.79	15.56
SW	16.23	40.66	46.53	35.36	21.04	31.3	34.97	12.15
NW	9.51	24.13	28.55	12.61	12.97	17.94	16.8	6.77
b) The regional spillover of embodied CO_2 emissions for 2002								
NE	68.55	97.52	65.72	41.82	21.24	34.59	27.71	9.91
NC	50.56	142.61	95.43	52.42	55.01	52.38	48.57	17.35
EC	25.02	63.19	61.8	55.07	21.29	41.81	33.39	10.91
SC	11.68	31.79	42.78	4.79	10.02	18.14	21.28	4.61
YER	37.47	93.87	74.16	32.52	23.98	37.79	35.51	15.08
YAR	24.95	58.61	76.51	32.86	26.9	32.49	31.25	9.74
SW	22.65	63.24	50.44	35.01	23.21	31.22	45.27	12.34
NW	10.82	23.55	23.29	9.41	12.57	16.56	16.16	12.32
c) The regional spillover of embodied CO_2 emissions for 2007								
NE	139.68	180.6	129.05	120.66	76.77	62.12	51.77	19.5
NC	151.34	333.11	432.5	183.17	204.08	135.66	108.72	38.17
EC	74.31	153.58	154.71	199.64	101.02	98.37	68.68	21.91
SC	28.42	86.38	95.18	24.96	44.31	36.86	34.66	8.57
YER	103.61	294.98	259.56	141.92	102.66	130.78	87.36	33.59
YAR	61.35	138.65	140.79	99.66	83.76	70.1	67	20.2
SW	48.16	93.43	112.02	87.11	65.16	57.71	81.27	19.17
NW	20.46	41.39	44.36	35.77	26.06	22.04	23.69	13.67

Table 7
The provincial direct CO_2 emissions for 3 years (million tons CO_2).

Province	Region	1997	2002	2007	Province	Region	1997	2002	2007
JL	NE	105.65	99.02	179.55	HE	YER	142.10	169.83	430.78
LN	NE	198.35	211.10	343.31	NM	YER	103.51	137.98	356.93
HL	NE	136.57	121.04	195.70	UB	YAR	132.85	154.07	248.87
BJ	NC	56.87	65.83	89.63	HU	YAR	95.07	86.45	223.33
TJ	NC	54.21	69.83	109.07	JX	YAR	49.64	54.70	108.45
HB	NC	203.05	274.05	514.56	AH	YAR	112.30	114.22	198.54
SD	NC	191.90	254.25	691.31	YN	SW	52.04	65.88	155.85
SH	EC	101.56	126.51	168.17	GZ	SW	62.35	76.68	174.86
JS	EC	191.09	223.73	473.64	SC	SW	114.93	115.01	197.56
ZJ	EC	117.42	155.31	327.45	CQ	SW	56.46	69.34	98.49
FJ	SC	41.23	66.95	160.22	GX	SW	50.09	51.39	118.49
GD	SC	153.55	214.53	389.47	GS	NW	46.37	55.33	96.36
HA	SC	7.61	11.90	20.90	QH	NW	10.23	13.79	19.99
SA	YER	62.85	71.68	143.10	NX	NW	16.38	47.50	67.87
SX	YER	151.14	228.79	334.57	SJ	NW	58.58	58.61	98.56

3.2.2. Effects of carbon spillover on provincial emissions

The above discusses the effects of interregional trade on regional CO_2 emissions, and this section provides detailed analysis from the provincial perspective. According to the approach and data provided in Section 2, we obtain the direct CO_2 emissions of each province. The results are shown in Table 7.

In 1997, the province with the highest direct CO_2 emissions is Hebei (203.05 million tons), followed by Liaoning (198.35 million tons) and Shandong (191.90 million tons). All the provinces are concentrated around the Bohai sea region, and the regions with high CO_2 emissions spread to the surrounding provinces, such as Henan, Shanxi, and Inner-Mongolia for the next 10 years (1997–2007). These provinces have abundant coal resources and are an important energy base for China. At the same time, another high direct emission region emerges gradually in the southeast part of China, which is made up of Guangdong, Hunan, Hubei, Anhui, Zhejiang and Jiangsu. However Jiangxi and Fujian, which are surrounded by this region, have relatively low direct CO_2 emissions.

According to Eq. (10), we calculate the emission balance of each province to present the effects of interprovincial trade on regional CO_2 emissions. The results are shown in Table 8.

Table 8 presents the impact of interprovincial trade on regional CO_2 emissions. The increase of the absolute value from 1997 to 2007 means that the interregional trade plays an increasingly important role in regional CO_2 emissions with the increase of trade volume within China. The signs of emission balance of most provinces are consistent for 3 years, which means the impact is relatively continuous. However, there are exceptions, such as Shandong. The reason is that, in 2007, the high carbon intensity sector, such as electricity production, holds a larger proportion in the export structure. In addition, the provinces with positive signs are mainly located in the southern and eastern coastal regions and most central and western provinces have negative signs. It means interprovincial trades increase the direct CO_2 emissions of the less developed provinces in the central and western regions.

Comparison analysis between Tables 7 and 8 shows that most provinces with large direct CO_2 emissions correspond to negative carbon emission balance, meaning that interprovincial trade contributes to the direct CO_2 emissions of these provinces. For instance, the contribution of trade to direct CO_2 emissions of Hebei, reaches as much as 253.28 million tons, almost half of Hebei's direct CO_2 emissions. It means interprovincial trade has obvious effects on regional direct CO_2 emissions. At the same time, some provinces, such as Guangdong province, benefit from interprovincial trade.

Excluding the effects of trade on provincial CO_2 emissions, we can obtain the regional CO_2 emissions under the consumption accounting principle, according to Eq. (9). It shows that the province with the highest CO_2 emissions is also mainly located in two regions: the first is Guangdong located in the Pearl River Delta region, whose CO_2 emissions under the consumption accounting principle reaches as much as 848.92 million tons in 2007; the second is the Yangtze River Delta region, made up of Shandong, Jiangsu and Zhejiang. Benefitting from China's reform and opening up strategy, the two regions are the most developed regions with large demand market.

The moving of regions with high CO_2 emissions from provinces around Bohai Sea region under the production accounting principle to the southeastern region under the consumption accounting principle means that trade within China contributes to the transfer of direct CO_2 emissions from southeastern provinces with large economic scales to

Table 8
The provincial CO_2 emission balance for 3 years (million tons CO_2).

Province	Region	1997	2002	2007	Province	Region	1997	2002	2007
JL	NE	−42.28	−56.54	−39.29	HE	YER	−1.3	−21.66	−93.06
LN	NE	−50.98	−65.56	−79.32	NM	YER	−57.88	−75.41	−232.83
HL	NE	−3.88	6.74	−34.22	UB	YAR	−0.49	−14.73	−55.36
BJ	NC	14.88	94.27	159.83	HU	YAR	18.13	9.89	−33.83
TJ	NC	−1.95	1.04	34.32	JX	YAR	5.91	11.08	55.71
HB	NC	−58.07	−107.47	−253.38	AH	YAR	−92.87	−34.57	−34.4
SD	NC	14.08	72.21	−205.38	YN	SW	10.18	10.84	−40.23
SH	EC	29.86	−0.75	114.46	GZ	SW	−6.99	−31.63	−94.24
JS	EC	76.56	59.01	86.96	SC	SW	5.75	11.35	43.3
ZJ	EC	43.06	119.39	294.52	CQ	SW	−21.66	−28.28	15.3
FJ	SC	33.11	29.69	75.46	GX	SW	22.76	13.47	35
GD	SC	140.43	79.13	459.45	GS	NW	−6.36	−10.32	−24.99
HA	SC	13.94	9.98	−1.35	QH	NW	4.33	4.61	7.99
SA	YER	1.11	9.12	−9.31	NX	NW	−3.15	−19.26	−37.35
SX	YER	−66.5	−68.2	−115.43	SJ	NW	−19.74	−7.45	1.69

Table 9
The provincial CO_2 emissions sub-balance for 3 years (million tons CO_2).

Province	Region	1997			2002			2007		
		$BAE_{1,r}$	$BAE_{2,r}$	$BAE_{3,r}$	$BAE_{1,r}$	$BAE_{2,r}$	$BAE_{3,r}$	$BAE_{1,r}$	$BAE_{2,r}$	$BAE_{3,r}$
JL	NE	−59.72	42.17	−8.78	−74.86	76.64	0.89	−240.48	128.68	−55.90
LN	NE	−16.63	5.50	−5.57	−19.20	3.72	−7.74	−6.58	19.72	6.57
HL	NE	−33.61	−20.05	−26.83	−6.46	−31.32	−18.89	−77.94	−18.00	−47.97
BJ	NC	12.20	−34.24	−11.02	73.79	−45.89	13.95	86.06	−76.56	4.75
TJ	NC	−2.96	−7.01	−4.99	0.66	−3.04	−1.19	52.81	−78.17	−12.68
HB	NC	−41.74	42.00	0.13	−49.83	71.43	10.80	−132.01	195.75	31.87
SD	NC	44.09	−64.05	−9.98	37.27	−25.28	6.00	−86.61	53.97	−16.32
SH	EC	35.29	−33.17	1.06	26.57	−11.82	7.38	131.32	−116.07	7.63
JS	EC	83.51	−99.62	−8.06	65.90	−71.18	−2.64	116.37	−118.95	−1.29
ZJ	EC	29.55	−25.02	2.27	90.40	−49.51	20.45	95.34	−46.78	24.28
FJ	SC	34.47	−62.53	−14.03	27.54	−23.28	2.13	48.26	−51.62	−1.68
GD	SC	108.62	−113.41	−2.40	90.18	−83.57	3.31	418.32	−323.16	47.58
HA	SC	8.40	−6.36	1.02	2.90	−1.89	0.51	2.26	−9.58	−3.66
SA	YER	−9.16	2.21	−3.48	−9.00	3.16	−2.92	−11.68	−15.36	−13.52
SX	YER	−51.95	46.90	−2.53	−37.01	49.42	6.21	−63.19	49.67	−6.76
HE	YER	1.36	−22.53	−10.59	−2.20	1.37	−0.42	−22.03	−17.50	−19.77
NM	YER	−37.33	41.40	2.04	−22.12	54.80	16.34	−105.87	151.02	22.58
UB	YAR	4.07	−17.79	−6.86	−18.12	17.70	−0.21	−20.76	7.88	−6.44
HU	YAR	8.48	−20.18	−5.85	13.48	−15.03	−0.78	−42.28	12.71	−14.79
JX	YAR	−0.10	−4.64	−2.37	2.93	−5.19	−1.13	18.07	−15.60	1.24
AH	YAR	−208.64	107.22	−50.71	−36.89	33.88	−1.51	−93.19	67.08	−13.06
YN	SW	−0.82	−6.48	−3.65	−5.49	−0.73	−3.11	−44.98	24.95	−10.02
GZ	SW	−35.40	20.89	−7.26	−20.01	23.46	1.73	−98.40	72.77	−12.82
SC	SW	1.55	−9.07	−3.76	5.69	−6.16	−0.24	25.43	−32.85	−3.71
CQ	SW	−31.37	20.61	−5.38	−56.54	49.86	−3.34	−45.91	17.24	−14.34
GX	SW	21.12	−18.34	1.39	20.20	−9.04	5.58	32.35	−34.88	−1.27
GS	NW	−12.74	1.01	−5.87	−20.85	13.53	−3.66	2.38	−0.56	0.91
QH	NW	0.46	−1.41	−0.48	2.94	−2.69	0.13	6.67	−3.69	1.49
NX	NW	−4.73	2.51	−1.11	−37.59	23.82	−6.89	−47.44	35.03	−6.21
SJ	NW	−56.27	23.48	−16.40	−5.39	1.74	−1.83	−14.76	4.37	−5.20
Total	–	−210.01	−210.01	−210.01	38.91	38.91	38.91	−118.49	−118.49	−118.49

the provinces around Bohai Sea with relatively abundant resources, which is consistent with the conclusion of Section 3.2.1 that interprovincial CO_2 emission transfer mainly concentrate in the coastal region.

3.3. National perspective

Previous studies analyze China's CO_2 emissions from different angles and give different explanations. For instance, coal dominates China's energy structure, export level increases quickly, rapid urbanization, and so on. This paper attempts to discuss this topic from another perspective: the pollution haven hypothesis. The less developed regions of China tend to have less strict environmental regulations, which induce high pollution industries to concentrate here and increases national CO_2 emissions. This section attempts to present the effect of interprovincial trade on total CO_2 emissions and to clarify provincial contribution and sectoral efficiency.

3.3.1. Provincial contribution to national CO_2 emissions

According to Eqs. (12), (13) and (14), we obtain the sub-balance CO_2 emissions of each province from import, export and comprehensive perspectives. The results are summarized in Table 9.

From the national perspective, the pollution haven hypothesis only holds in 2002. However, the increase of national CO_2 emissions is relatively small, amounting to only 38.91 million tons. Compared with the total national CO_2 emissions in 2002 (3465.30 million tons), the impact of interprovincial trade on national CO_2 emissions is almost negligible. In 1997 and 2007, interprovincial trade contributes to the reduction of total CO_2 emissions by 210.01 and 118.49 million tons, respectively. The changing trend of the influence of interregional trade on national CO_2 emissions can be explained from the perspective of industrial reallocation these years.

From 1997 to 2002, China experienced a sharp decrease in the carbon intensity. However, Table 9 shows that some coastal provinces (such as Beijing, Fujian, Guangdong) reduce their carbon intensity through importing from inland provinces (such as Shanxi, Guizhou, Jilin) with higher carbon intensities. This means, at the beginning of the West Development Strategy, which started in 2000, energy intensive firms took up a huge proportion. However, in the period of 2002–2007, this situation changed gradually, and we can see the sign of several provinces (such as Fujian, Shandong, and Guizhou) change from positive to negative. The policy implication is that during the process of industrial reallocation inland provinces should focus on the new and high technology industries, rather than the traditional energy intensive industries.

From the provincial perspective, $BAE_{3,r}$ of Table 9 shows the comprehensive effects of interprovincial trade on China's total CO_2 emissions, and $BAE_{1,r}$ and $BAE_{2,r}$ further present this influence from perspective of import and export. Table 9 shows that the main contributors to national CO_2 emissions are the coastal provinces with large economic scale, such as Guangdong and Zhejiang, and central regions with higher carbon intensity, such as Inner-Mongolia. With lower carbon intensity, coastal provinces would contribute to total CO_2 emissions if they import from other provinces with higher carbon intensity. The central regions are just the opposite. The policy suggestions for the coastal regions are increasing the environmental regulations on imported products to encourage the interprovincial exporters to apply environmentally effective technology. The most effective method for the central provinces is reducing their own carbon intensity. In other words, different policies should be adopted according to the influence mechanisms of different provinces.

3.3.2. Sectoral contribution to national CO_2 emissions

This section presents the provincial sub-balance and national emission balance from the sectoral perspective. The sectoral contributions to provincial CO_2 emissions are shown in Fig. 4.

Fig. 4 shows that for 3 years, the sectors with great energy intensities contribute most to the regional CO_2 emissions, such as EP, MS, PC, and CM. The unbalanced distribution of China's fossil resources determines that energy intensive firms are mainly located in the coastal and

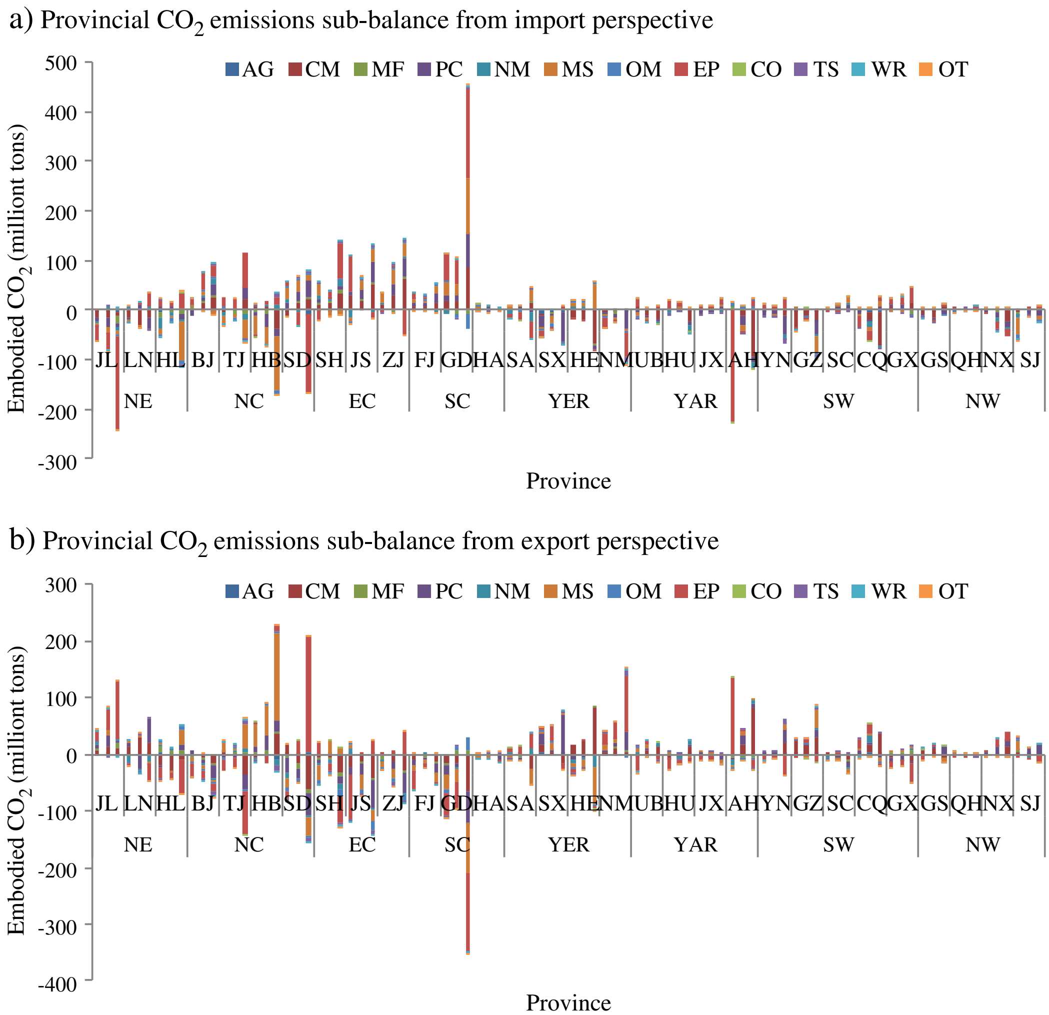

Fig. 4. The sectoral contribution to provincial CO_2 emissions sub-balance.

western provinces, with less developed technology and higher carbon intensity. Although the coastal provinces can reduce their CO_2 emissions through importing products from other provinces, it contributes to an increase in the national total CO_2 emissions, because interregional trade results in greater increase in the CO_2 emissions of the less developed provinces. Then we discuss the sectoral contribution to national CO_2 emissions. According to Eqs. (15) and (16), we obtain the sectoral sub-balances, shown in Table 10.

In 1997, most sectors have a negative sub-balance, with the exception of the mining sector. It means interprovincial trade decrease total CO_2 emissions for most sectors. Before 2005, the existence of a large number of small mines means that the mining sector is less efficient. In 2005, China began to rectify the coal-mining sector, and a large number of small mines were closed. Therefore, the condition of the mining sector changed in 2007. At the same time, the sector that most contributes to the decrease of total CO_2 emissions is sector electricity production. The provinces with the three highest electricity exports were Jiangsu, Fujian and Beijing in 1997. All of them are located in the coastal region with higher technology and lower carbon intensity, so the spatial distribution of electricity is environmentally efficient.

As the only year with a positive sign from a national perspective, the year 2002 has four less effectiveness sectors: EP, MS, CM and CO. The most obvious change is sector electricity production, compared with the results of 1997. The reason is that, in 2002, the electricity production base moved to central provinces with abundant coal resources, such as Inner-Mongolia and Shanxi. Although it reduces the transportation cost of coal resources, more CO_2 emissions are produced because central provinces have relatively higher carbon intensity.

In 2007, with the construction of the Three Gorges dam, Hubei became the province with the largest electricity exportation. Hydro power is a type of clean energy, so the electricity production sector of 2007 is relatively more effective than in 2002. In addition, the other two sectors with positive sign are MS and TS. However, it should be pointed out that the conditions for both MS and EP improve, compared with 2002 while that of sector TS becomes serious. It should be paid more attention in the future adjustment of industrial structure.

Table 10
The sectoral CO_2 emissions sub-balance for 3 years (million tons CO_2).

	AG	CM	MF	PC	NM	MS	OM	EP	CO	TS	WR	OT	Total
1997	−3.46	4.13	−7.49	−24.36	−41.87	−3.28	−21.52	−103.2	−0.32	−3.98	−2.88	−1.77	−210.01
2002	−5.28	23.99	−8.64	−10.28	−5.6	26.55	−12.57	38.9	0.08	−4.4	−0.55	−3.28	38.91
2007	−8.21	−21.95	−4.8	−16.05	−38.79	4.62	−27.81	0.45	−3.32	0.57	−0.51	−2.7	−118.49

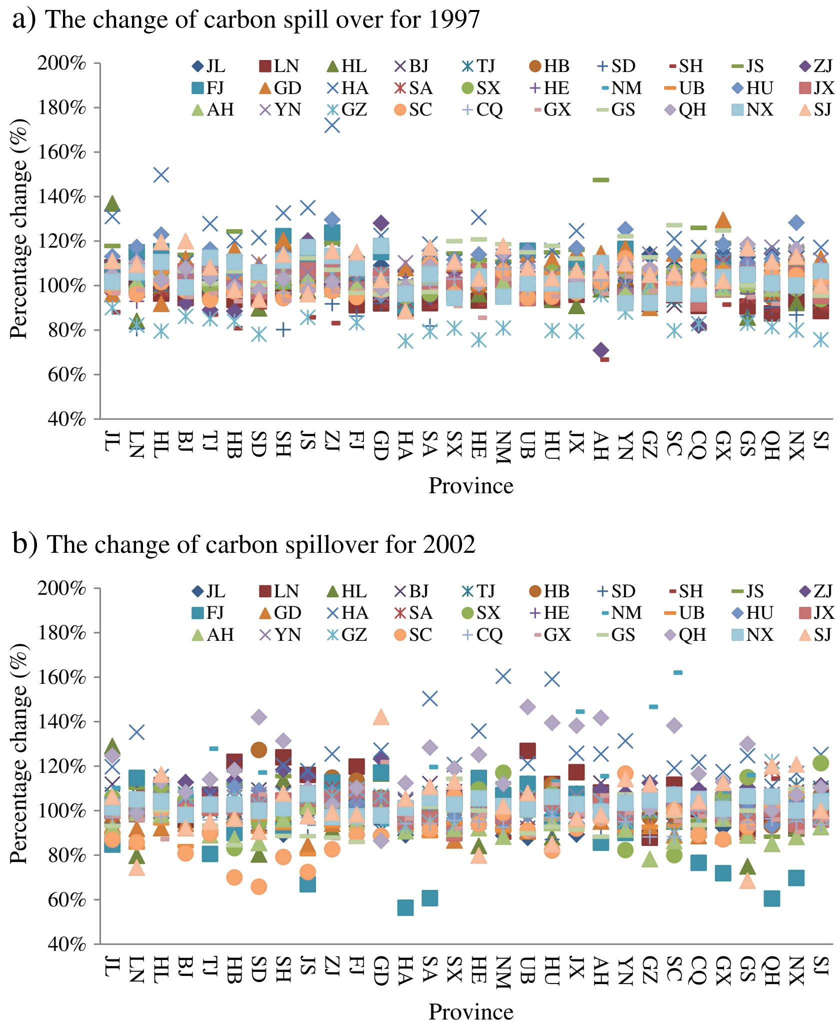

Fig. 5. The change of carbon spillover if the sectoral level increases from 12 to 28.

4. Discussion

4.1. Sensitivity analysis

Spatial and sectoral aggregation levels may influence the calculation results of embodied CO_2 emissions (Su and Ang, 2010; Su et al., 2010). Restricted by the sectoral level of interprovincial trade of 2007, this paper chooses a relatively smaller sectoral level of 12. This section provides the sensitivity discussion. In addition, due to data availability, we fail to discuss every regions of China, such as Hong Kong, which may affect the final results.

According to the original national energy consumption data from the Chinese National Bureau of Statistics (NBS, 1998, 2003), we further disaggregate the energy consumption data of 1997 and 2002 into 28 sectors. At the same time, the input–output tables and interprovincial trade tables are aggregated to the same sectoral level. According to the calculation methodology of Section 2, the percentage change of regional emission transfers of the 2 years are shown in Fig. 5.

Fig. 5 shows the influences of sectoral aggregation level have two characters. First, the simpler the trade structure is, the easier to be influenced by the sectoral aggregation level because the smaller sectoral aggregation level means it is more difficult to reflect the trade structure, such as Qinghai. Secondly, the smaller the trade volume is, the more sensitive is the calculation results to the sectoral aggregation level, such as Hainan, which is separated from other provinces by the Qiongzhou Strait. These two characters determine that influence of sectoral aggregation level on the total carbon emission embodied in interregional trade is not significant. We can see most of the provincial spillover data do not change significantly with the increase of sectoral aggregation level. In 1997 and 2002, and the embodied CO_2 emissions increase by 2.93% and 1.50% respectively, when the carbon aggregation level increases from 12 to 28.

From the spatial perspective, this paper has a detailed spatial division that reaches as much as 30 provinces, but some regions are not analyzed because of data acquisition problems. The interregional trade between inland provinces and these regions may influence the final results. Here we qualitatively discuss the possible influences with Hong Kong as an example.

With a mature service sector, Hong Kong has a smaller volume of direct CO_2 emissions. In 2010, the total direct CO_2 emissions volume of Hong Kong was only 36.29 million tons, and it presented a decreasing trend year by year.[3] However, the trade scale between Hong Kong and inland provinces were increasing quickly these years, and Hong Kong mainly imported energy-intensive products. This means the trade between Hong Kong and inland provinces contribute to a carbon leakage from Hong Kong to inland provinces. Since Hong Kong has lower carbon intensity than the inland provinces, the trade between them may contribute to an increase in total CO_2 emissions.

[3] The data are obtained from United Nations Statistics Division. Millennium Development Goals indicators: Carbon dioxide emissions (CO_2), thousand metric tonnes of CO_2 (collected by CDIAC) http://mdgs.un.org/unsd/mdg/SeriesDetail.aspx?srid=749&crid=.

Table 11
Comparison with previous estimates (million tons CO_2).

	NE		NM		NC		EC		SC		CE		NW		SW	
a) The calculation results of the present paper and Su and Ang's (2014) study (presented inside the parentheses) for 1997																
Northeast (NE)	44.06		15.08		40.24		49.15		30.17		54.09	(12.20)	21.78		29.06	
North Municipalities (NM)	9.81		5.57		20.74		19.48		12.14		22.08	(4.30)	10.33		13.15	
North Coast (NC)	23.95		22.24		36.84		71.88		59.49		67.38	(30.80)	27.23		32.06	
East Coast (EC)	19.04		15.80		48.98		56.54		78.36		65.35	(28.00)	26.42		33.21	
South Coast (SC)	12.84		6.68		14.30		41.60		7.67		28.88	(9.30)	10.57		18.42	
Central (CE)	39.11	(17.80)	31.10	(16.10)	71.14	(28.00)	150.23	(76.90)	79.03	(36.70)	90.09		46.62	(23.10)	55.07	(30.10)
Northwest (NW)	21.45		15.82		38.14		57.78		26.23		54.77	(22.40)	23.92		32.32	
Southwest (SW)	16.23		13.94		26.72		46.53		35.36		42.63	(13.10)	21.86		34.97	
b) The calculation results of the present paper and Meng et al.'s (2013) study (presented inside the parentheses) for 2002																
Northeast (NE)	68.55		32.74	(16.81)	64.79	(19.19)	65.72	(5.25)	41.82	(5.53)	45.83	(9.86)	19.92	(10.64)	27.71	(7.72)
North Municipalities (NM)	15.06	(2.33)	18.61		23.44	(14.02)	21.17	(1.63)	15.66	(1.04)	21.31	(2.57)	11.45	(2.38)	18.39	(1.49)
North Coast (NC)	35.50	(10.40)	44.19	(48.08)	56.37		74.26	(9.01)	36.76	(4.93)	61.02	(13.93)	30.97	(12.94)	30.18	(3.80)
East Coast (EC)	25.02	(3.44)	28.31	(7.97)	34.88	(17.28)	61.80		55.07	(11.48)	53.64	(35.02)	20.37	(9.64)	33.39	(8.42)
South Coast (SC)	11.68	(3.33)	15.26	(4.22)	16.53	(6.63)	42.78	(8.62)	4.79		23.51	(12.14)	9.25	(8.71)	21.28	(12.75)
Central (CE)	42.43	(16.30)	39.59	(29.88)	75.05	(39.94)	118.17	(46.16)	50.04	(24.02)	72.37		36.92	(29.65)	48.22	(15.40)
Northwest (NW)	30.81	(9.95)	28.96	(14.11)	32.43	(14.13)	55.79	(11.78)	24.75	(6.20)	45.55	(14.23)	32.57		34.71	(11.03)
Southwest (SW)	22.65	(12.43)	32.74	(10.63)	30.51	(11.26)	50.44	(13.87)	35.01	(18.20)	41.36	(15.84)	25.41	(30.41)	45.27	
c) The calculation results of the present paper and Meng et al.'s (2013) study (presented inside the parentheses) for 2007																
Northeast (NE)	139.68		61.08	(26.53)	119.51	(66.05)	129.05	(47.44)	120.66	(25.28)	105.35	(78.88)	53.04	(19.00)	51.77	(24.92)
North Municipalities (NM)	35.61	(7.45)	33.65		48.45	(39.76)	42.11	(10.94)	35.20	(5.68)	54.58	(15.85)	32.60	(5.34)	25.51	(6.30)
North Coast (NC)	115.73	(31.15)	130.17	(54.53)	120.84		390.39	(69.33)	147.97	(34.50)	193.35	(114.9)	97.38	(31.20)	83.21	(33.52)
East Coast (EC)	74.31	(6.79)	55.19	(4.77)	98.39	(19.32)	154.71		199.64	(29.71)	154.55	(60.15)	66.75	(9.79)	68.68	(14.94)
South Coast (SC)	28.42	(11.66)	38.54	(4.95)	47.84	(14.94)	95.18	(29.80)	24.96		63.26	(45.39)	26.47	(14.76)	34.66	(42.22)
Central (CE)	108.33	(19.84)	84.12	(17.52)	199.49	(89.66)	281.37	(157.1)	169.80	(49.90)	183.71		116.93	(27.98)	107.80	(35.27)
Northwest (NW)	77.09	(25.00)	66.79	(20.00)	124.62	(71.56)	163.35	(75.33)	107.55	(41.46)	130.90	(101.9)	71.33		70.25	(49.42)
Southwest (SW)	48.16	(16.95)	32.30	(7.70)	61.13	(26.65)	112.02	(41.74)	87.11	(32.47)	89.47	(69.61)	52.57	(29.18)	81.27	

Table 12
Comparison with previous studies (million tons CO_2).

	Carbon emissions embodied in regional/national exports	Avoided carbon emissions by regional/national imports	Balance of avoided emissions
Weber et al. (2008)	580 (1997; national); 760 (2002; national)	700 (1997; national); 1170 (2002; national)	−120 (1997; national) −410 (2002; national)
Zhang (2012)	620 (1997; national); 755 (2002; national); 1751 (2007; national)	817 (1997; national) 762 (2002; national) 1020 (2007; national)	−197 (1997; national) −7 (2002; national) 721 (2007; national)
This present paper	2294 (1997; regional); 2391 (2002; regional); 6226 (2007; regional)	2504 (1997; regional); 2352 (2002; regional); 6344 (2007; regional)	−210 (1997; regional); 39 (2002; regional); −119 (2007; regional)

4.2. Comparison with previous studies

This section compares the results of this study with that from previous studies. Comparisons on CO_2 emissions embodied in interregional trade are made with Meng et al.'s (2013) paper and Su and Ang's (2014) study. And we make comparisons with Weber et al.'s (2008) study and Zhang's (2012) study to compare the pollution haven hypothesis from the perspectives of interregional and international trade.

For comparison, this section adopts the same region classification method of previous studies (Meng et al., 2013; Su and Ang, 2014) (Tibet is not analyzed in this present paper).[4] The spillover of embodied emissions for 1997 are compared between the estimated results of this present paper and Su and Ang's (2014) study, and the latter focuses on the distribution and absorption pattern of the central region. The estimated results of this present paper for 2002 and 2007 are compared with Meng et al.'s (2013) paper. The results are shown in Table 11.

Su and Ang (2014) state that the estimate of embodiments in international exports can be greatly affected by the chosen of EEBT or MRIO approaches for the interregional trade because of interregional feedback effects (Su and Ang, 2011). This study shows that this conclusion is also held for the interregional trade. The EEBT approach would allocate some parts of the national total CO_2 emissions to interregional trade (Su and Ang, 2011); therefore, the estimated results of this present paper are greater than previous studies (Meng et al., 2013; Su and Ang, 2014) that adopt the MRIO approach. There are other factors that may contribute to the difference on calculation results. For instance, three studies are based on different data bases. The multi-regional input–output tables of Meng et al.'s (2013) study are compiled by the China State Information Center (Zhang and Qi, 2012), Su and Ang's (2014) study adopts the data constructed by the Institute of Developing Economics-Japan External Trade Organization (IDE-JETRO, 2003), and this paper's multi-regional input–output tables are constructed by the Development Research Center of the State Council, P.R.C. (Li et al., 2010; Xu and Li, 2008).

Both interregional and international trades influence the total CO_2 emissions, and we further compare the effects of the trade within China on total emissions and that of the international trade. The results are shown in Table 12.

We can see the volume of CO_2 emissions embodied in the interregional trade is greater than that embodied in the international trade obviously, but there is no significant difference between the international and interregional emission balances. The greater gross volume of CO_2 emissions embodied in interregional trade can be explained from the

[4] The division of eight regions is provided in Table 1 of Su and Ang's study (2014) and Table A1 of Meng et al.' study (2013).

closer economic link within a country than that among different nations. However, the balance of avoided emissions is not only determined by the trade volume but also by the trade structure and carbon intensities. As a major export country, China has huge trade surplus. At the same time, the carbon-intensity difference between China and the rest of the world is greater than that among different provinces within China. The lower regional trade deflects and smaller carbon intensity disparities determine that the difference on the balance of avoided emissions between interregional and international trade is not as significant as the gross embodied emission volumes. For instance, Yan and Yang (2010) state the global CO_2 emissions would increase by 0.71–3.76% resulting from China's foreign trade, while the interregional trade within China only contributes to an increase of total emissions by 1.77% in 2002.

5. Conclusions

With its rapid economic development, China has become the world's largest CO_2 emitter and the world's second largest economy. This paper discusses the effects of interprovincial trade on spatial distribution and total volume of China's CO_2 emissions. We extend previous empirical studies by calculating the embodied CO_2 emissions of two representive periods of Chinese economy. For the first period, China's carbon intensity decreased sharply; and for the second period, China's total CO_2 emissions increased quickly. We enrich the existing studies by parceling the pollution haven hypothesis into another approach of multi-regional input–output analysis (EEBT approach, and Lopez et al. (2013) discuss the MRIO approach), to clarify the provincial contributions and the sectoral efficiency. The main conclusions are shown as below.

Determined by the sharp decrease in carbon intensity of the first period and the quick increase in trade volume of the second period, China's CO_2 emissions embodied in interprovincial trade remain relatively stable for the first 5 years (from 2293.72 million tons in 1997 to 2390.71 million tons in 2002) and increase sharply for the second 5 years (6225.90 million tons in 2007). Provinces and sectors with large scales of embodied CO_2 emissions mainly concentrate in the coastal region and the second industry. With the rapid economic growth and expanding domestic demand, trade scale within China will increase quickly in the future. China should pay much more attention to the effects of interprovincial trade on regional and national CO_2 emissions, especially the interprovincial trade between coastal and inland provinces.

In recent years, it is becoming increasingly obvious that interprovincial trade contributes to the carbon reduction of the southern and eastern coastal regions, while central and western provinces with relatively abundant fossil resources and high carbon intensity bear the shifted carbon reduction responsibility. To reach the carbon reduction target that CO_2 emissions per unit of GDP reduce by 40% to 45% from the level of 2005 by 2020, China should determine the provincial carbon reduction responsibility based on the consumption accounting principle, which prevents developed regions from reducing regional CO_2 emissions by importing from other less developed provinces with higher carbon intensity.

Interprovincial trade contributes to the reduction of national CO_2 emissions in both 1997 and 2007, and the pollution haven hypothesis only holds in 2002. Provinces that import or export carbon intensive products, and sectors that are mainly located in regions with high carbon intensity, should be responsible for the pollution haven hypothesis. The first type of provinces should adopt more serious environmental regulations on imported products, and the second type should try to reduce carbon intensity. At the same time, as one of China's important strategies, the adjustment of the industrial structure has great significance for carbon reduction. The results indicate that China should not only raise the proportion of the tertiary industry in the national economy but also optimize the industrial spatial distribution, especially for the sectors with higher carbon intensity.

There are several potential extensions of this study that are worthy of pursuit. First, this study only discusses CO_2 emissions embodied in direct interprovincial trade and fails to reflect interregional feedback effects. This may results in an overestimation on the CO_2 emissions embodied in trade. Secondly, this paper chooses a relative smaller sectoral aggregation level, under the restriction of interprovincial trade table of 2007; therefore future studies are expected to estimate more detailed interprovincial trade tables. Thirdly, this paper proposes a methodology to clarify the regional and sectoral responsibility to the pollution haven hypothesis, which can be implemented to other regions.

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Appendix A. Supplementary data

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References

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

Bordigoni, M., Hita, A., Blanc, L.G., 2012. Role of embodied energy in the European manufacturing industry: application to short-term impacts of a carbon tax. Energy Pol. 43, 335–350.

CESY, 1998, 2003, 2008. China energy statistical yearbook, National Bureau of Statistics of China, National Development and Reform Commission. China Statistics Press, Beijing, China.

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

Copeland, B.R., Taylor, M.S., 2004. Trade, growth, and the environment. J. Econ. Lit. 42 (1), 7–71.

Dietzenbacher, E., Mukhopadhyay, K., 2007. An empirical examination of the pollution haven hypothesis for India: towards a green Leontief paradox? J. Environ. Res. Econ. 36, 427–449.

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

Feng, K., Davis, S.J., Sun, L., Li, X., Guan, D., Liu, W., Hubacek, K., 2013. Outsourcing CO_2 within China. Proceedings of the National Academy of Sciences of the United States of America (PNAS), p. 110.

Gavrilova, O., Vilu, R., 2012. Production-based and consumption-based national greenhouse gas inventories: an implication for Estonia. Ecol. Econ. 75, 161–173.

Guan, D., Liu, Z., Geng, Y., et al., 2012. The gigatonne gap in China's carbon dioxide inventories. Nat. Clim. Change 2 (9), 672–675.

Guo, J.E., Zhang, Z.K., Meng, L., 2012. China's provincial CO_2 emissions embodied in international and interprovincial trade. Energy Pol. 42, 486–497.

IDE-JETRO, 2003. Multi-regional input-output model for China, statistical data series, No. 86, Institute of Developing Economies. JETRO.

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

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., 1998. Primary energy and greenhouse gases embodied in Australian fiPri consumption: an input–output analysis. Energy Pol. 26, 495–506.

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

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

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.

Liu, J., Yang, H., 2009. China fights against statistical corruption. Science (New York, NY) 325, 675–676.

Lopez, L.A., Arce, G., Zafrilla, J.E., 2013. Parcelling virtual carbon in the pollution haven hypothesis. Energy Econ. 39, 177–186.

Meng, L., Guo, J., Chai, J., et al., 2011. China's regional CO_2 emissions: characteristics, interregional transfer and emission reduction policies. Energy Pol. 39, 6136–6144.

Meng, B., Xue, J., Feng, K., Guan, D., Fu, X., 2013. China's inter-regional spillover of carbon emissions and domestic supply chains. Energy Pol. 61, 1305–1321.

National Bureau of Statistics of China (NBS), 1998. China Energy Statistical Yearbook, National Development and Reform Commission. China Statistics Press, Beijing, China.

National Bureau of Statistics of China (NBS), 2003. China Energy Statistical Yearbook, National Development and Reform Commission. China Statistics Press, Beijing, China.
Pan, J., Phillips, J., Chen, Y., 2008. China's balance of emissions embodied in trade: approaches to measurement and allocating international responsibility. Oxf. Rev. Econ. Policy 24, 354–376.
Peters, G.P., 2007. Opportunities and challenges for environmental MRIO modeling: illustrations with the GTAP database. 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. Ecol. Econ. 65, 13–23.
Peters, G.P., Weber, C.L., Guan, D., et al., 2007. China's growing CO_2 emissions a race between increasing consumption and efficiency gains. Environ. Sci. Technol. 41 (17), 5939–5944.
Sinton, J.E., 2001. Accuracy and reliability of China's energy statistics. China Econ. Rev. 12 (4), 373–383.
Sinton, J.E., Fridley, D.G., 2000. What goes up: recent trends in China's energy consumption[J]. Energy Pol. 28 (10), 671–687.
Su, B., Ang, B.W., 2010. Input–output analysis of CO2 emissions embodied in trade: the effects of spatial aggregation. Ecol. Econ. 70 (1), 10–18.
Su, B., Ang, B.W., 2011. Multi-region input–output analysis of CO2 emissions embodied in trade: the feedback effects. Ecol. Econ. 71, 42–53.
Su, B., Ang, B.W., 2013. Input–output analysis of CO2 emissions embodied in trade: competitive versus non-competitive imports. EnergyPol. 56, 83–87.
Su, B., Ang, B.W., 2014. Input–output analysis of CO2 emissions embodied in trade: a multi-region model for China. Appl. Energy 114, 377–384.
Su, B., Huang, H.C., Ang, B.W., Zhou, P., 2010. Input–output analysis of CO2 emissions embodied in trade: the effects of sector aggregation. Energy Econ. 32 (1), 166–175.
Su, B., Ang, B.W., Low, M., 2013. Input–output analysis of CO2 emissions embodied in trade and the driving forces: processing and normal exports. Ecol. Econ. 88, 119–125.
Tan, H., Sun, A., Lau, H., 2013. CO_2 embodiment in China–Australia trade: the drivers and implications. Energy Pol. 61, 1212–1220.
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. Ecol. Econ. 62, 37–44.
United Nations, 1999. Handbook of input–output table compilation and analysis. Studies in Methods Series F, No 74. Handbook of National Accounting. United Nations.
Weber, C.L., Peters, G.P., Guan, D., et al., 2008. The contribution of China's exports to climate change. Energy Pol. 36, 3572–3577.
Wiedmann, T., 2009. A review of recent multi-region input–output models used for consumption-based emission and resource accounting. Ecol. Econ. 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. Ecol. Econ. 61, 15–26.
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. Econ. Syst. Res. 22, 19–42.
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. Ecol. Econ. 70, 1937–1945.
Xu, X.C., Li, S.T., 2008. The Construction and Application of Chinese Regional Input–Output Table of 1997. Tsinghua University Press, Beijing.
Yan, Y., Yang, L., 2010. China's foreign trade and climate change: a case study of CO2 emissions. Energy Pol. 38, 350–356.
Zhang, Y.G., 2009. Structural decomposition analysis of sources of decarbonizing economic development in China: 1992–2006. Ecol. Econ. 68, 2399–2405.
Zhang, Y., 2012. Scale, technique and composition effects in trade-related carbon emissions in China. Environ. Resour. Econ. 51, 371–389.
Zhang, Y., Qi, S., 2012. China's Interregional Input–Output Tables for 2002 and 2007. China Statistics Press, Chinese.
Zhang, M., Mu, H., Ning, Y., Song, Y., 2009. Decomposition of energy-related CO_2 emission over 1991–2006 in China. Ecol. Econ. 68, 2122–2128.