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Abstract

The present study analyzed the consumption-based carbon emissions from fossil fuel consumption of Beijing in 2012. The multi-scale input–output analysis method was applied. It is capable of tracing the carbon emissions embodied in imports based on a global multi-regional input–output analysis using Eora data. The results show that the consumption-based carbon emission of Beijing has increased by 18% since 2007, which is 2.57 times higher than the production-based carbon emission in 2012. Only approximately 1/10 of the total carbon emissions embodied in Beijing's local final demand originated from local direct carbon emissions. Meanwhile, more than 4/5 were from domestically imported products. The carbon emission nexus between Beijing and other Chinese regions has become closer since 2007, while the imbalance as the carbon emission transfer from Beijing to other regions has been mitigated. Instead, Beijing has imported more carbon emissions from foreign countries. Some carbon emission reduction strategies for Beijing concerning different goals are presented on the basis of detailed discussion.

1. Introduction

Cities play an important role in achieving greenhouse gas (GHG) mitigation targets. Beijing is a typical international megacity. Analyzing the GHG emissions that are embodied in the final demand and trade of Beijing could help us understand the carbon supply chain of a city and facilitate the relevant policy-making. While China has promised to reach its emission peak before 2030, Beijing, as the capital of China, would need to share the responsibility. Exploring the close carbon relationship between Beijing and other Chinese regions could benefit the carbon emission mitigation of China as a whole.

Over the last few decades, many studies have been conducted to analyze Beijing's carbon emissions. Under the national GHG inventories framework of the Intergovernmental Panel on Climate Change (IPCC), some of these studies focused on the territorial production-based carbon emissions of Beijing. Detailed direct GHG emission inventories concerning different sources of carbon have been presented. The trends and driving forces have been discussed [1–5]. Beijing has made great efforts to achieve the energy-saving and emission-reduction goal. Despite some fluctuations, the energy-related CO_2 emissions of Beijing have stabilized at approximately 100–110 Mt yr^{-1} (including urban and rural household consumption). Additionally, the declining trend of the secondary industrial sector's carbon emissions has been reported in some studies [1, 3, 5].

To properly distribute the responsibility for reducing carbon emissions, some studies focused further on Beijing's consumption-based carbon emissions. These studies applied either a single region input–output analysis (SRIO) method [6, 7] or a multi-regional input–output analysis (MRIO) method with Beijing represented as a Chinese region or a municipality

[8–13]. Both methods have advantages and disadvantages. The SRIO studies focused only on Beijing's local emissions and aimed to reveal the dependency relationships among local industries. It only required a small amount of economic and carbon emission data. In the SRIO studies of Beijing, the carbon emission embodied in imports is usually ignored [7]. A few studies have assumed that the imported product has the same carbon emission as the local product, and the emissions avoided by imports have been calculated [6].

Unlike the SRIO, the present application of MRIO concerning the sub-national economy of China aimed at investigating the total carbon emissions triggered by each economy's final demand. It is capable of tracing both local and exotic consumption-based emissions and can actually calculate the carbon emission embodied in trade. Feng *et al* connected China MRIO table to GTAP global input–output data to discuss the outsourcing CO_2 within China in 2007 [10]. Wang *et al* made great progress by constructing a time series of MRIO tables for 30 Chinese provinces and 185 world countries between 1997 and 2011 [14]. The data requirement to support a complete MRIO analysis is high. However, the detailed trade data among different Chinese regions as well as those among Chinese regions and foreign countries are usually hard to obtain. Some assumptions must be made. For example, the gravity model is usually applied to estimate the trade among different Chinese regions [15].

As a compromise of both SRIO and MRIO, a multi-scale input–output (MSIO) analysis method was used to analyze the carbon emissions of Beijing [16, 17]. Databases on the average embodied carbon emission intensity for the world and for national economies have been used to estimate the carbon emissions embodied in international and domestic trade. Since it can distinguish between the different embodied carbon emissions of imported products and local products, the MSIO is superior to the SRIO. In theory, the MSIO is not as accurate as the MRIO. But it requires much less data than a complete MRIO analysis does. When the MRIO data are not available or reliable, the MSIO can be served as an efficient and a relative advantaged way (comparing to SRIO) to analyze consumption-based carbon emissions. Since the data requirements of the MRIO model increase sharply when the number of regions increases, the advantage of MSIO will be even more prominent if we need to conduct an input–output analysis for a sub-sub-national or even a small economy.

This study aims to analyze the consumption-based carbon emissions of the Beijing economy in 2012 based on an input–output analysis. No study concerning the Beijing economy in 2012 has been reported yet. Beijing usually trades a large amount of products with foreign countries (international trade) and other Chinese regions (domestic trade). It is important for Beijing to determine the carbon emissions embodied in trade to achieve the targeted carbon emission reduction goal and design a low-carbon development strategy through the supply chain. As no MRIO table of China for 2012 has been published yet, the MSIO method was applied to analyze Beijing's consumption-based carbon emissions. The results were compared with those of 2007 to detect the trends and new features of Beijing's energy-related carbon emission. It can help Beijing adjust its carbon emission reduction strategy.

2. Methodology and materials

2.1. MSIO analysis

The MSIO method was developed by Chen and his colleagues [16, 18–20]. Figure 1 shows the related carbon emission input and output flows of a typical industrial sector i in the Beijing economy.

The production of the Beijing economy is simultaneously sustained by local products and domestic and foreign imports, and $z_{j,i}^{L}$, $z_{j,i}^{D}$, and $z_{j,i}^{M}$ represent local products, domestic imports and foreign imports, respectively, from Sector j that are used as intermediate inputs for local Sector i. $z_{i,j}^{L}$ represents the local products from Sector i that are used as intermediate inputs for local Sector j. y_{i}^{L} represents the local products from Sector i to satisfy the local final use. The local products from local Sector i that satisfy the external use in the domestic economic system and the foreign economic system are represented as domestic exports, $e_{i,d}^{L}$, and foreign exports, $e_{i,m}^{L}$. Finally, x_i represents the total output of the ith local sector, and the basic economic balance of Sector i can be written as

$$x_i = \sum_{j=1}^{n} z_{i,j}^{L} + y_i^{L} + e_{i,d}^{L} + e_{i,m}^{L}. \quad (1)$$

Some ecological indicators related to Sector i are defined to analyze the carbon emission flows accompanied by the above economic activities. F_i represents the carbon directly emitted by the ith local sector. ε_j^{L}, ε_j^{D}, and ε_j^{M} are used to represent the embodied carbon emission intensities of the local products from Sector j, domestically imported products from Sector j of the rest of the country, and foreign-imported products from Sector j of the rest of the world, respectively. Here, the embodied carbon emission intensity is principally defined as the marginal carbon emission when the total amount of a product changes by an incremental unit. According to conservation law, the physical embodied carbon emission balance equation for local Sector i can be written as

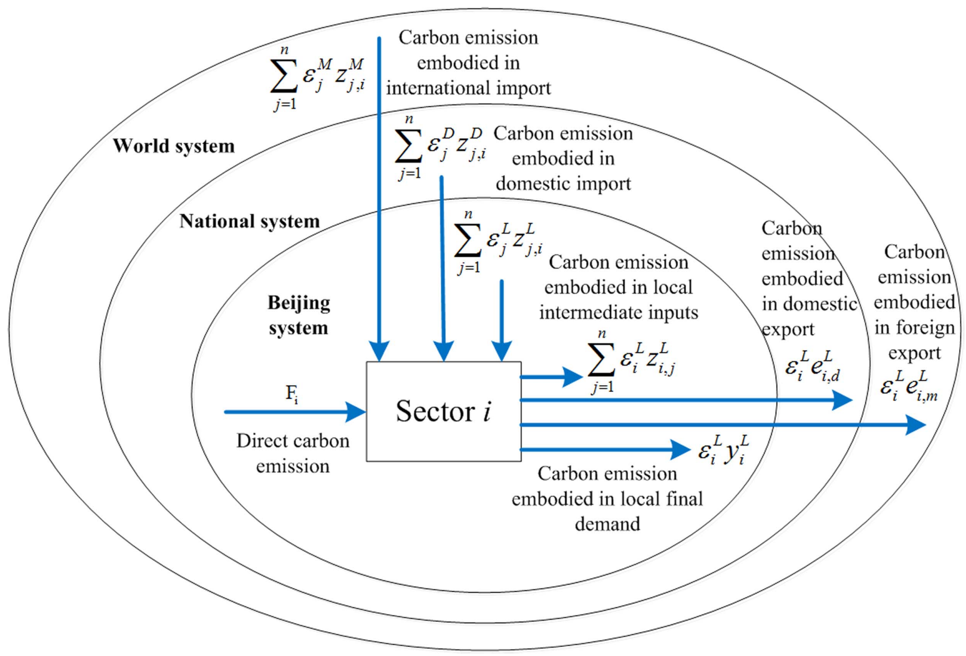

Figure 1. The embodied carbon emission flow of an industrial sector in the Beijing economy.

$$F_i + \sum_{j=1}^{n} \varepsilon_j^L z_{j,i}^L + \sum_{j=1}^{n} \varepsilon_j^D z_{j,i}^D + \sum_{j=1}^{n} \varepsilon_j^M z_{j,i}^M = \varepsilon_i^L x_i. \quad (2)$$

For the entire economic system, an aggregate matrix equation can be induced as

$$\mathbf{F} + \boldsymbol{\varepsilon}^{\mathbf{L}}\mathbf{Z}^{\mathbf{L}} + \boldsymbol{\varepsilon}^{\mathbf{D}}\mathbf{Z}^{\mathbf{D}} + \boldsymbol{\varepsilon}^{\mathbf{M}}\mathbf{Z}^{\mathbf{M}} = \boldsymbol{\varepsilon}^{\mathbf{L}}\mathbf{X}, \quad (3)$$

in which

$$\mathbf{F} = [F_i]_{1\times n},$$
$$\boldsymbol{\varepsilon}^{\mathbf{L}} = [\varepsilon_i^L]_{1\times n},\ \boldsymbol{\varepsilon}^{\mathbf{D}} = [\varepsilon_i^D]_{1\times n},\ \boldsymbol{\varepsilon}^{\mathbf{M}} = [\varepsilon_i^M]_{1\times n},$$
$$\mathbf{Z}^{\mathbf{L}} = [z_{i,j}^L]_{n\times n},\ \mathbf{Z}^{\mathbf{D}} = [z_{i,j}^D]_{n\times n},\ \mathbf{Z}^{\mathbf{M}} = [z_{i,j}^M]_{n\times n},$$

$\mathbf{X} = [x_{i,j}]_{n\times n}$, where $x_{i,j} = x_i$ when $i = j$, and $x_{i,j} = 0$ when $i \neq j$.

Thus, the embodied carbon emission intensity matrix for local products, as the basis for estimating the carbon emission transfer embodied in exports, can be given as

$$\boldsymbol{\varepsilon}^{\mathbf{L}} = (\mathbf{F} + \boldsymbol{\varepsilon}^{\mathbf{D}}\mathbf{Z}^{\mathbf{D}} + \boldsymbol{\varepsilon}^{\mathbf{M}}\mathbf{Z}^{\mathbf{M}})(\mathbf{X} - \mathbf{Z}^{\mathbf{L}})^{-1}. \quad (4)$$

After several deformations, equation (4) can also be rewritten as

$$\boldsymbol{\varepsilon}^{\mathbf{L}} = (\mathbf{F} + \boldsymbol{\varepsilon}^{\mathbf{D}}\mathbf{Z}^{\mathbf{D}} + \boldsymbol{\varepsilon}^{\mathbf{M}}\mathbf{Z}^{\mathbf{M}})\mathbf{X}^{-1}(\mathbf{I} - \mathbf{A}^{\mathbf{L}})^{-1}, \quad (5)$$

where $\mathbf{A}^{\mathbf{L}} = \mathbf{Z}^{\mathbf{L}}\mathbf{X}^{-1}$ is a coefficient matrix that describes the inputs in the production of these sectors, and $(\mathbf{I} - \mathbf{A}^{\mathbf{L}})^{-1}$ is the so-called Leontief inverse [21]. The equation is similar as that in previous environment extended input-output studies. Since part of the local intermediate inputs of Beijing is supplied by imported goods, some of the carbon emissions embodied in local products originate from external economies. Therefore, in this equation, the 'direct' carbon emission coefficient includes not only the coefficients that originated from direct local carbon emissions ($\mathbf{F}\mathbf{X}^{-1}(\mathbf{I} - \mathbf{A}^{\mathbf{L}})^{-1}$) but also the coefficients that originated from external carbon emission imports ($\boldsymbol{\varepsilon}^{\mathbf{D}}\mathbf{Z}^{\mathbf{D}}\mathbf{X}^{-1}(\mathbf{I} - \mathbf{A}^{\mathbf{L}})^{-1}$ and $\boldsymbol{\varepsilon}^{\mathbf{M}}\mathbf{Z}^{\mathbf{M}}\mathbf{X}^{-1}(\mathbf{I} - \mathbf{A}^{\mathbf{L}})^{-1}$). The whole of the three are the coefficients that are triggered by the final demand (internal and external) of the local products. $\varepsilon^{L,L}$, $\varepsilon^{L,D}$, and $\varepsilon^{L,M}$ are used to denote the local (with direct carbon emission), domestic (with domestically imported intermediate input), and global (with foreign-imported intermediate input) embodied carbon emission intensities of local products, respectively.

From equation (5), it can be known that the direct sectoral carbon emission data, the economic input-output table and the embodied carbon emission intensity matrixes for imported products are the preconditions for obtaining the overall carbon emission initiated by the consumption of local products. As long as the embodied carbon emission intensity of local products is obtained, the carbon emissions embodied in the final demand, the exports and the embodied carbon emission balance of the trades can be calculated accordingly.

2.2. Data sources

To reveal and analyze the carbon emission budget of the Beijing economy in 2012, a three-scale embodied carbon emission input–output analysis was performed based on the MSIO method illustrated in section 2.1. The official economic input–output table for the Beijing economy in 2012 was adopted as the base economic data of the MSIO analysis. This monetary input–output table is in units of Chinese Yuan (referred to as Yuan hereafter). There are 42 industrial sectors in the table (see appendix, table A1). As a noncompletive input–output table, it does not distinguish between local and imported products. Both intermediate use and final consumption have been divided into three parts based on the proportion of total local output, domestic import, and foreign import. It is assumed that the imported products have been distributed to intermediate input and final use at the same ratio as the local products. For example, the foreign-imported intermediate input–output matrix, $\mathbf{Z^M}$, can be calculated as

$$z_{i,j}^M = z_{i,j}\left(\frac{x_i^M}{x_i + x_i^D + x_i^M}\right), \quad (6)$$

where $z_{i,j}$ is the total intermediate input from Sector i to Sector j, x_i is the total output of Sector i, x_i^D is the domestically imported economic flow of Sector i, and x_i^M is the foreign-imported economic flow of Sector i. Meanwhile, the final demand of Sector i from foreign imports, $\mathbf{F^M}$, is expressed as

$$f_{i,k}^M = f_{i,k}\left(\frac{x_i^M}{x_i + x_i^D + x_i^M}\right), \quad (7)$$

where $f_{i,k}$ is the kth final consumption of Sector i.

Much work have been done to compile direct carbon emission inventory of an economy [22–26]. We are only concerned with the CO_2 emissions caused by fossil fuel consumption in this study. The direct carbon emission inventory is calculated from energy balance data and each sector's energy consumption data with reference to the Beijing Statistical Yearbook 2013 [27], which can be found on our online database [28, 29]. The default carbon emission factors of IPCC were applied to calculate the combustion-based carbon emissions of 14 types of fossil fuels.

The embodied carbon emission intensity databases for the domestic and foreign-imported products of the Beijing economy are critical base data for the three-scale input–output analysis of the Beijing economy. A MRIO analysis for the world economy in 2012 was performed to obtain them. Both the input–output data and direct carbon emission inventory of all countries were from the Eora global MRIO database [30, 31]. The embodied carbon emissions by fossil fuel consumption for 26 sectors in 189 countries worldwide were analyzed. According to the multi-scale input−output scheme, the databases should represent the rest of the world excluding the Chinese economy (because the products from the Chinese economy are considered as domestically imported products) and the rest of China excluding the Beijing economy to estimate the carbon emissions transfer embodied in foreign and domestic imports.

With respect to the former, the output-weighted, average embodied carbon emission intensity database for the 26 sectors in the other 188 nations of the world economy was applied (see appendix, table A1). Because excluding the Beijing economy from the Chinese economy is difficult, the embodied carbon emissions intensity database for 26 sectors of the Chinese economy from the global MRIO analysis was approximated (see appendix, table A1). Because the share of the Beijing economy is a small part of the Chinese economy (the GDP ratio is approximately 3%), the deviation presented by the assumption can be ignored. To capture the detailed carbon emission flows of Beijing [32], we linked the 26 sectors in Eora to 42 sectors in the Beijing economy (see appendix, table A1). As a result, in some sectors, the products in world economy and the Chinese economy were exported to more than one sector in the Beijing economy. Because the intensity is averaged for all outputs of the sector, the process would not result in much deviation in estimating the carbon emissions embodied in imports.

3. Results

3.1. Carbon emissions by the fossil fuel consumption of Beijing in 2012

In 2012, the direct carbon emissions by fossil fuel consumption of the Beijing economy were estimated as 9.13E + 07 t CO_2 (not including the emissions by direct energy consumption of urban and rural households). It was slightly lower than that in 2007 (9.45E + 07 t CO_2) [17], revealing that Beijing controlled the direct or territory-based carbon emissions well. As the largest emitter among the 42 sectors, Sector 25 (PSE: Production and Supply of Electric Power and Heat Power) emitted 2.95E + 07 t CO_2, accounting for 32% of the total direct carbon emissions. Sector 30 (TSP: Transportation, Storage, Posts and Telecommunications) was the second largest emitter, contributing 24% to the total emissions. Apart from these two sectors, the share of each of the remaining sectors is less than 5%. The two largest sectors should be emphasized when developing Beijing's production-based carbon emission reduction strategies.

Approximately 2.35E + 08 t CO_2 was embodied in the local final demand of Beijing in 2012, 2.57 times higher than the direct carbon emission. Although the direct carbon emission of Beijing has been slightly reduced, the embodied carbon emission of Beijing has increased by 18% since 2007 [17]. In 2007, the production-based carbon emissions of Beijing was approximately a half of the consumption-based carbon emissions. In 2012, the ratio fell to 39%. The increasing gap between production-based and consumption-based carbon emissions indicates that Beijing has involved more carbon emission transfer issues.

Beijing's local final demand includes rural household consumption, urban household consumption, government consumption, fixed capital formation, and inventory increase. In addition, local products are also exported to other Chinese regions and foreign

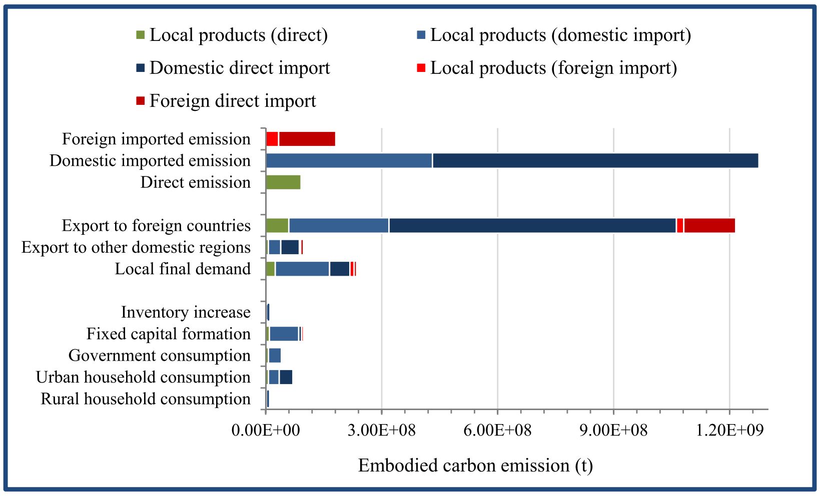

Figure 2. Embodied carbon emissions related to the Beijing economy in 2012.

countries. Together they form the final use of local products (see figure 2). Three sources of Beijing's carbon emissions, direct emission, domestic-imported emission and foreign-imported emission, are differentiated in figure 2. In 2012, in addition to the direct carbon emission (6%), Beijing imported 1.28E + 09 t CO_2 (82%) and 1.81E + 08 t CO_2 (12%) from other regions in China and other countries, respectively. Among the total amount of 1.55E + 09 t CO_2 emissions related to Beijing (direct carbon emission plus domestically imported carbon emission plus foreign imported carbon emission), over 3/4 was exported to other regions in China, approximately 6% was exported to other countries, and only approximately 15% was embodied in the local final demand. Beijing can be seen as a key carbon emissions node of China, which maintains close carbon relationships with other Chinese regions.

As for the local final demand, fixed capital formation embodied the largest carbon emission (42% of the total emission embodied in local final demand), and urban household consumption ranked second in the list (32%), followed by the emissions embodied in government consumption (20%), inventory increase (3%) and rural household consumption (3%). Although the order is the same as that in 2007, the carbon emissions gap between fixed capital formation and other types of local final demand has been narrowed (the proportion has declined from 54% to 42%). The ratio of Beijing's urban population to the rural population was only approximately 6.25 in 2012, but the carbon emissions embodied in urban household consumption were approximately 12.66 times higher than the embodied carbon emission of rural household consumption. Thus, urban residents caused more carbon emissions than rural residents.

3.2. Embodied carbon emission flows of Beijing 2012

The core principal of input–output analyses is attributing the production-based carbon emission to the consumption-based final demand. The imported products were assumed to have been distributed to intermediate inputs and final uses at the same ratio as local products in this work. Therefore, Beijing's local final demand appeared to be simultaneously met by foreign-imported products, domestically imported products and local products. As for the local products, because their production involves domestic and foreign imported intermediate inputs, part of the carbon emissions embodied in the local products of Beijing also originate from other Chinese regions or other countries. Therefore, the carbon emissions embodied in the local final demand of Beijing have five sources (which are also presented in figure 2): (1) local direct carbon emission (LE^L); (2) embodied carbon emission of domestically imported products that are directly used to meet the local final demand (DIE_d^L); (3) embodied carbon emission of domestically imported products that are used as intermediate inputs, i.e., indirectly used to meet the local final demand (DIE_i^L); (4) embodied carbon emission of foreign-imported products that are directly used to meet the local final demand (FIE_d^L); and (5) embodied carbon emission of foreign-imported products that are used as intermediated inputs, i.e., indirectly used to meet the local final demand (FIE_i^L).

On the basis of economic trade matrixes and the related embodied carbon emission intensity databases of the Beijing economy, all embodied carbon emission flows related to the Beijing economy were calculated, and they are illustrated in figure 3. According to the results, only approximately 1/10 of the total carbon emissions embodied in Beijing's local final demand

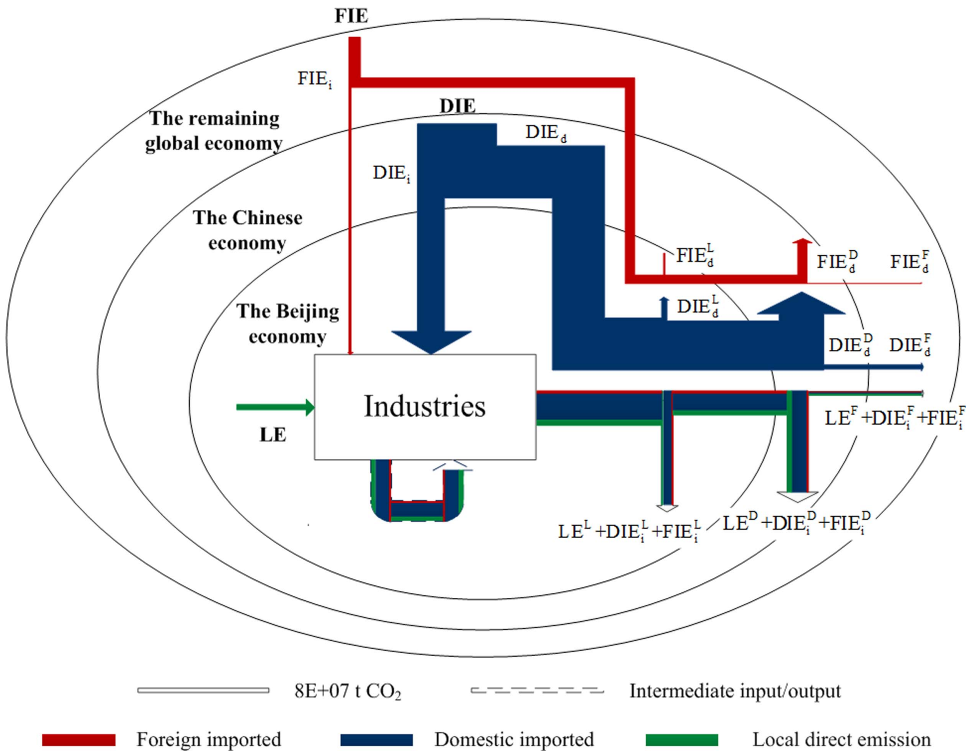

Figure 3. The embodied carbon emissions flows of the Beijing economy in 2012 (LE: local emission; FIE: foreign imported emission; DIE: domestically imported emission; superscript L/D/F: emission embodied in local final demand/domestic export/foreign export; subscript d: direct imported emission; subscript i: indirect imported emission through imported intermediate inputs).

originated from local direct carbon emissions, while more than 4/5 were from domestically imported products. The invisible or indirectly embodied carbon emission of local products to meet the local final demand originating from domestically imported intermediate inputs (DIE_i^L) was approximately three times higher than the obvious or direct one (DIE_d^L). The situation for the foreign-imported carbon emissions embodied in the local final demand was similar (FIE^L); the ostensible (FIE_d^L) and unapparent embodied carbon emissions (FIE_i^L) are 6.37E + 06 t CO_2 and 1.07E + 07 t CO_2, respectively.

The carbon emissions embodied in domestic and foreign export products also have five sources as the local final demand (the symbols are similar to those aforementioned in the last paragraph for local final demand, and subscript L has been replaced with D and M to denote domestic final use and foreign final use, respectively). Except for the embodied carbon emissions originating from the direct local carbon emission (DE^D and DE^F) and the direct re-exported domestic (DIE_d^D and DIE_d^F) and foreign-imported products (FIE_d^D and FIE_d^F), a significant portion of the domestic and foreign exports' embodied carbon emission supplied by local products also originated from domestic (DIE_i^D and DIE_i^F) and foreign-imported intermediate inputs (FIE_i^D and FIE_i^F). The embodied carbon emissions of local products and domestic and foreign imports accounted for 7%, 82%, and 11%, respectively, of the total domestic export carbon emission. With respect to the foreign export embodied carbon emission, the ratios were more or less the same.

3.3. Carbon emission embodied in Beijing trade in 2012

In 2012, Beijing was a net importer with net domestic and foreign-imported emissions of 6.00E + 07 t CO_2 and 8.36E + 07 t CO_2, respectively. Figure 4 shows the carbon emissions embodied in domestic trade of all industry sectors (the full name of each sector can be found in appendix, table A2). In 2012, Beijing imported 1.28E + 09 t CO_2 from other Chinese regions, which was slightly higher than domestically exported embodied carbon emission (1.22E + 09 t CO_2). Compared with 2007 [17], on the one hand, the carbon emissions transfer between Beijing and other Chinese regions has become closer since 2007 (the total amount of carbon emission embodied in domestic import and export has increased by 5.64 and 9.21 times, respectively); on the other hand, the imbalance brought by the carbon emission transfer from Beijing to other Chinese regions has been mitigated (the ratio of domestically imported carbon emission to export has decreased from 1.71 in 2007 to 1.05 in 2012, and the net domestically imported carbon emission decreased from 9.40E + 07 t CO_2 in 2007 to 6.00E + 07 t CO_2 in 2012).

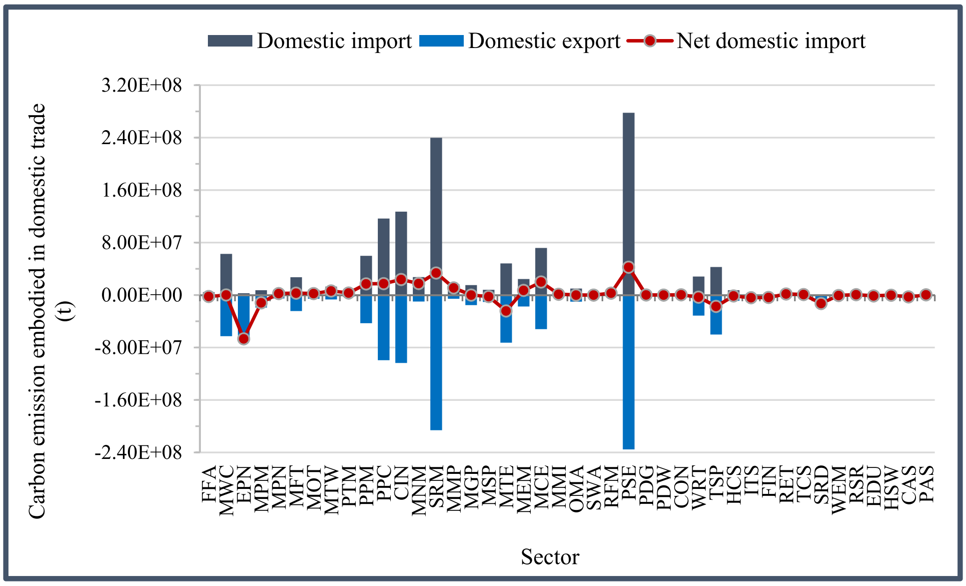

Figure 4. The carbon emission embodied in domestic trade.

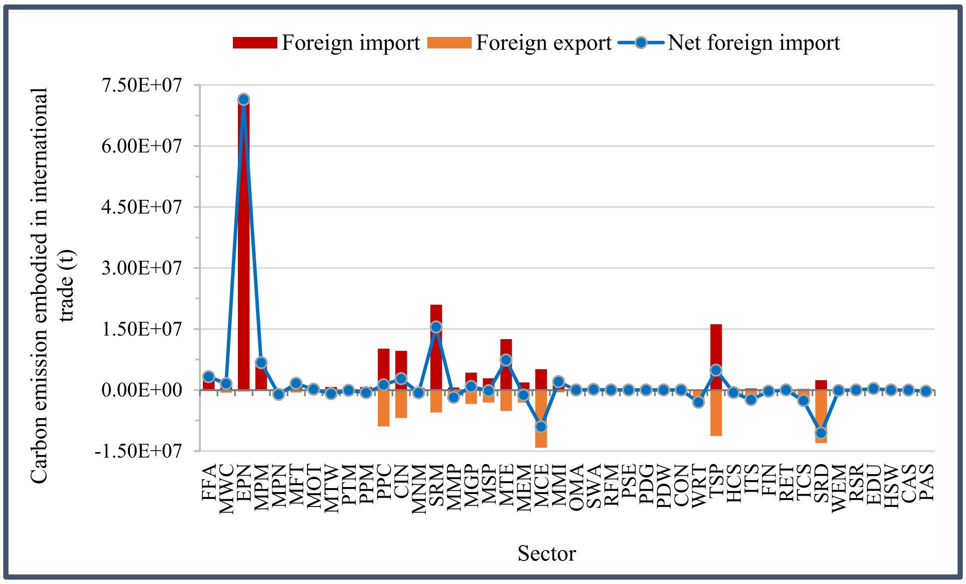

Figure 5. The carbon emission embodied in international trade.

Sector 25 (PSE: Production and Supply of Electric Power and Heat Power) had the largest domestic import, export and net imported embodied carbon emissions, and it plays a key role in the carbon nexus between the Beijing economy and other Chinese regions. Sector 3 (EPN: Extraction of Petroleum and Natural Gas) had the largest net domestic exported embodied carbon emission among the 42 industries. This may be due to the large share of Sector 3 (16%) in the total economic value of Beijing's domestic export. Meanwhile, the input–output data show that Sector 3's domestic export is approximately 76 times higher than its domestic import. The essential reason may be that the headquarters of many state-owned energy enterprises are located in Beijing, and many of their outputs have been attributed to Beijing.

Figure 5 shows the carbon emission embodied in international trade of all industry sectors (the full name of each sector can be found in appendix, table A1). In 2012, Beijing imported 1.81E + 08 t CO_2 from foreign countries, which was approximately 1.86 times higher than the foreign-exported carbon emissions (9.75E + 07 t CO_2). The carbon emissions embodied in the foreign imports and exports of Beijing increased by 2.28 and 1.42 times in 2012 compared with those in 2007, respectively. The development was relatively lower than that of domestic trade. Unlike domestic trade, however, the international carbon emission transfer imbalance has been aggravated (the ratio of internationally imported carbon emission to export has increased from 1.16 in 2007 to 1.86 in 2012, and the ratio of net domestically imported carbon emission to the international one has decreased from 8.79 in 2007 to 0.72 in 2012). This indicates the growing internationalization of Beijing.

Among the 42 sectors, Sector 3 (EPN: Extraction of Petroleum and Natural Gas) had the largest foreign-imported as well as net foreign-imported embodied carbon emissions. Additionally, Sector 20 (MCE: Manufacture of Communication Equipment, Computer and Other Electronic Equipment) had the largest foreign-exported embodied carbon emission. Sector 36 (SRD: Scientific Research and Development, Technical Services) has the largest net foreign-exported embodied carbon emission. This is because Beijing imported a large amount of petroleum and natural gas while exporting many relatively high-tech products and services.

4. Discussions

4.1. Advantages of this work

With the acceleration of globalization, cooperation, and specialization in the world economy, ever-increasing international and interregional trade has made the consumption-based carbon emission of an urban economy increasingly difficult to analyze. The difficulty mainly lies in the estimation of the carbon emissions embodied in imports and exports. This study focused on the trade issue and made progress in the following:

(1) The estimation of the carbon emission embodied in imports plays a key role in input–output analyses [33, 34]. Due to the variation in technological efficiency and the diversity of economic structures, the same types of products that are produced in different economies emit different carbon emissions during their production. As the capital of China and an international megacity, Beijing imports many products from other Chinese regions and foreign countries to sustain its production and consumption. The MRIO is capable of addressing this problem; the same products from different countries are treated as completely different types of products [35]. However, there is no available MRIO data for China in 2012.

This work applied the method of MSIO to distinguish between different carbon emissions of imports and local products. The average carbon emission intensity data for the rest of the global economy (not including the Chinese economy) and China were applied to estimate the carbon emissions embodied in foreign imports and domestic imports, respectively. Some SRIO studies utilized the 'emissions avoided by imports (EAI)' to discuss the effect of imported carbon emissions on the local economy [36]. The EAI_d (emissions avoided by domestic imports) of Beijing in 2012 is estimated to only account for 60% of DIE in this paper. In addition, the EAI_f (emissions avoided by foreign imports) is approximately 1.40 times as many carbon emissions as FIE in this paper. The average carbon productivity (output per unit carbon emission) of the Beijing economy is hence higher than that of the Chinese economy but somewhat lower that of the rest of the world.

(2) Intermediate trade plays an important role in today's global exchange [37]. Although Beijing is neither a free port nor a production center of China, it is a key intermediary between other Chinese regions and foreign countries. Beijing has been reported to have the highest degree of dependency on intermediate trade among all Chinese regions in the mainland since 1994 [38]. In 2013, the domestic-foreign re-export trade (the domestic import that was ultimately exported to foreign countries) accounted for 47% of Beijing's total export, and the foreign-domestic re-export trade (the foreign import that was ultimately exported to other domestic regions) accounted for 73% of Beijing's import [38].

In former studies, the imports have usually been attributed to intermediate input and local final demand, but not to export [32, 33, 36]. In this work, we assumed that both domestic and foreign-imported products are distributed to intermediate inputs and final use (including domestic and foreign export) at the same ratio as local products. The re-export issue as an important feature of the Beijing economy has been addressed. Approximately 62% and 78% of the carbon emissions embodied in domestic imports and foreign imports, respectively, are estimated to have been re-exported to other Chinese regions and foreign countries (see DIE_d^D DIE_d^F, FIE_d^D and FIE_d^F in figure 3).

(3) Climate change is essentially a global issue. However, the distribution of responsibility for reducing carbon emissions has, as a result of political negotiation, its local characteristics. For example, under the Kyoto Protocol framework, some Annex I countries have transferred carbon emissions to other countries by means of trade, which has led to the carbon leakage and carbon imbalance problems. The MSIO enabled us to directly estimate the virtual imported carbon emission that accompanies imported products. Furthermore, the embodied carbon emission flows identified can help in designing carbon emission reduction strategies for Beijing as a combination of multiple responsible entities holding different opinions.

If reducing Beijing's local carbon emission is the priority, local intensity ($\varepsilon^{L,L}$) is sufficient (all three intensities of the 42 sectors in 2012 are listed in appendix, table A2), and we must import products with high local intensity to reduce as much of the local carbon emission as possible regardless of whether the products are from other Chinese regions or foreign countries. The Chinese central government would probably launch a binding emission target for each region in the future, and according to our results, Beijing should enlarge its imports of Sector 4 (MPM: Mining and Processing of Metal Ores) and Sector 25 (PSE: Production and Supply of Electric Power and Heat Power).

However, if we consider the entire Chinese economy to reduce China's carbon emission, the second carbon emission source, i.e., domestically imported carbon emission, should also be considered. We may argue that Beijing should enlarge its foreign imports while both local and domestically imported intensities should be applied to maximize profit. Our findings have verified that Beijing has been doing this since 2007 by shifting domestic-imported carbon emissions to foreign-imported emissions. In addition, in the future, Beijing is recommended to enlarge its foreign import of Sector 13 (MNM: Manufacture of Nonmetallic Mineral Products) and Sector 14 (SRM: Smelting and Rolling of Metals) in addition to Sector 25 and Sector 4. For the entirely different matter of global climate change mitigation, we should allocate the production of high-intensity products to economies with high carbon emission productivity. Whether Beijing should import or where it should import from should also depend on its carbon emission performance among all global economies.

4.2. Descriptions about uncertainties in MSIO model and dataset

Current paper connects to several uncertainties to certain degree. Firstly, as sectoral-based trade data of different Chinese regions and those among Chinese regions and foreign countries are not available, assumptions become unavoidable regarding China-global MRIO database. The domestic trades among different Chinese regions were usually estimated by the gravity model [15], and the sectoral structure of provincial foreign trade were assumed to be the same as that of China's foreign trade [10, 14]. Meanwhile, uncertainties also exist when connecting China MRIO data to a world MRIO table, especially in sector aggregation, spatial aggregation and imports technology [39], which all require further research and more comprehensive datasets. In order to retain efficiency and accuracy, the MSIO was proposed to estimate the carbon emissions embodied in international and domestic trades of a city economy based on the average embodied carbon emission intensity for the world and for national economies. This method not only distinguishes embodied carbon emissions of imported products from local products, making it superior to SRIO, but also requires much less data than a complete MRIO analysis. Although a MSIO turns to be less accurate than a MRIO, such statement is under the precondition in the accuracy of MRIO dataset. Without an accurate and complete MRIO database, the MSIO can be served as an alternative, compromised but still efficient method to address regional environmental issues against a background of global climate change in our study.

Secondly, data requirements of the MRIO model increase sharply as the number of regions increases while the MSIO can be easily applied to a sub-sub-national or even a small-scale economy. The obtained intensity datasets of MSIO are important basis data to analyze life-cycle resource uses and environmental pollutions of local engineering [18, 40–43]. Considering the high data requirement, the MRIO-based results will be served only as a basis database to discuss the uncertainty of our work. Further research can be implemented to compare modelling and results differences between MSIO and MRIO model when the MRIO 2012 for China is constructed.

Thirdly, aggregation and disaggregation can lead different results in input–output studies. Several theoretical studies have discussed the effects of sector and spatial aggregations [32, 44–48]. Sector aggregation usually requires correct mathematical method, rather than data. Sector disaggregation requires extensive supplementary data [49–51]. In the present work, Beijing 2012 MSIO table is in a format of 42 sectors. The international trade flow data from MSIO can be aggregated and link to the Eora 26-sector global MRIO database. Other global MRIO database is also available, such as GTAP MRIO model which consists of 57 sectors. Comparatively speaking, linking MSIO trade data with GTAP MRIO would require more data for disaggregation and produce uncertainties.

5. Conclusions

The analysis of Beijing's carbon emissions can be very useful for developing carbon emission reduction strategies for both China and other cities. Although the production-based and consumption-based carbon emissions of Beijing have been intensively studied, no study on 2012 emissions has been reported. Considering that the MRIO data for China is not yet available, this study applied the method of MSIO to analyze the energy-related carbon emission of Beijing in 2012. The framework and algorithm of MSIO are presented in detail in section 2.1. This method can distinguish between the different carbon emissions embodied in imports and local products. Moreover, it requires much less data than a complete MRIO analysis does. As a fundamental step, a global MRIO analysis was conducted based on Eora data. Additionally, the output-weighting averaged embodied carbon emission intensity database for the 26 sectors in the other 188 nations (excluding China) of the world economy was applied to estimate the carbon emissions embodied in the foreign imports of Beijing. Meanwhile, the database for the Chinese economy as a part of the MRIO analysis results was applied to estimate the carbon emission of Beijing's domestic imports.

The production-based carbon emissions from the fossil fuel consumption of Beijing in 2012 is estimated as 9.13E + 07 t CO_2, which is slightly lower than that in 2007 (9.45E + 07 t CO2). On the contrary, the consumption-based carbon emission (2.35E + 08 t CO_2) has increased by 18% since 2007, which is 2.57 times higher than the production-based carbon emission in 2012. Among the total amount of 1.55E + 09 t CO_2 emissions that are related to Beijing, 6% are from direct carbon emissions, 82% are from domestically imported carbon emissions, and 12% are from domestically imported carbon emissions. Over 3/4 of these emissions have been exported to other regions in China, approximately 6% have been exported to other countries, and only approximately 15% have been embodied in Beijing's local final demand. Although fixed capital formation still embodied the largest carbon emission among five types of local final demand, its share has been greatly reduced from 54% in 2007 to 42% in 2012. The five sources of carbon emission embodied in the final use of Beijing were defined and calculated. The indirect carbon emission originating from imported intermediate inputs was found to play an important role in the embodied carbon emission of Beijing's local final demand.

In 2012, Beijing imported 1.28E + 09 t CO_2 and 1.81E + 08 t CO_2 from other Chinese regions and foreign countries, respectively. It also exported 1.22E + 09 t CO_2 and 9.75E + 07 t CO_2 to other Chinese regions and foreign countries, respectively. Compared with 2007, the carbon emission connection between Beijing and other Chinese regions has become closer, but the imbalance in the carbon emission transfer from Beijing to other regions has been reduced. Meanwhile, Beijing has imported more carbon emissions from foreign countries through international trade, which could benefit carbon emission reduction in China as a whole. The advantages of this study concerning the carbon emission analysis of imports and exports are discussed in the last section. Relevant policy suggestions are presented based on different carbon emission reduction needs.

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Appendix

Table A1. Embodied carbon emission intensity for 26 sectors of the world economy excluding the Chinese economy and the Chinese economy in 2012 (Unit: t/1E + 04 Yuan).

No.	Sector	World economy excluding the Chinese economy	Chinese economy
1	Agriculture	0.45	0.77
2	Fishing	0.51	0.75
3	Mining and Quarrying	0.63	2.13
4	Food & Beverages	0.59	1.35
5	Textiles and Wearing Apparel	0.82	1.81
6	Wood and paper	0.61	1.95
7	Petroleum, Chemical and Non-Metallic Mineral Products	1.03	2.86
8	Metal Products	1.08	2.98
9	Electrical and Machinery	0.65	2.11
10	Transport Equipment	0.63	2.18
11	Other Manufacturing	0.70	1.96
12	Recycling	0.59	0.15
13	Electricity, Gas and Water	5.71	14.34
14	Construction	0.55	2.00
15	Maintenance and Repair	0.23	0.76
16	Wholesale Trade	0.26	0.76
17	Retail Trade	0.28	0.76
18	Hotels and Restaurants	0.34	1.11
19	Transport	2.22	2.15
20	Post and Telecommunications	0.24	0.94
21	Financial Intermediation and Business Activities	0.17	0.77
22	Public Administration	0.30	0.82
23	Education, Health and Other Services	0.25	1.38
24	Private Households	0.15	1.18
25	Others	0.32	0.82
26	Re-export & Re-import	0.74	0.59

Table A2. Embodied carbon emission intensity and corresponding sector in Eora 26 of Beijing's 42 sectors (Unit: t/1E + 04 Yuan).

No.	Sector	Abbreviation	$\varepsilon^{L,L}$	$\varepsilon^{L,D}$	$\varepsilon^{L,M}$	Total	Sector in Eora 26
1	Farming, Forestry, Animal Husbandry and Fishery	FFA	0.47	0.88	0.10	1.45	1, 2
2	Mining and Washing of Coal	MWC	0.04	1.70	0.08	1.82	3
3	Extraction of Petroleum and Natural Gas	EPN	0.31	0.31	0.02	0.64	3
4	Mining and Processing of Metal Ores	MPM	1.58	1.36	0.26	3.20	3
5	Mining and Processing of Nonmetal Ores and Other Ores	MPN	0.05	0.75	0.09	0.89	3
6	Manufacture of Foods and Tobacco	MFT	0.24	0.99	0.11	1.34	4
7	Manufacture of Textile	MOT	0.26	1.45	0.12	1.84	5
8	Manufacture of Textile Wearing Apparel, Footwear, Caps, Leather, Fur, Feather(Down) and Its products	MTW	0.20	1.09	0.08	1.37	5
9	Processing of Timbers and Manufacture of Furniture	PTM	0.20	1.48	0.08	1.76	6
10	Papermaking, Printing and Manufacture of Articles for Culture, Education and Sports Activities	PPM	0.20	1.53	0.08	1.81	6
11	Processing of Petroleum, Coking, Processing of Nuclear Fuel	PPC	0.16	0.44	0.45	1.06	7
12	Chemical Industry	CIN	0.21	1.35	0.10	1.65	7
13	Manufacture of Nonmetallic Mineral Products	MNM	0.77	1.70	0.11	2.58	7
14	Smelting and Rolling of Metals	SRM	0.13	2.11	0.18	2.42	8
15	Manufacture of Metal Products	MMP	0.16	1.90	0.14	2.20	8
16	Manufacture of General Purpose Machinery	MGP	0.11	1.28	0.14	1.53	11
17	Manufacture of Special Purpose Machinery	MSP	0.11	1.25	0.14	1.50	11
18	Manufacture of Transport Equipment	MTE	0.08	1.09	0.15	1.32	10
19	Manufacture of Electrical Machinery and Equipment	MEM	0.09	1.39	0.12	1.61	9
20	Manufacture of Communication Equipment, Computer and Other Electronic Equipment	MCE	0.05	1.36	0.09	1.50	9
21	Manufacture of measuring instrument and meter	MMI	0.09	1.03	0.14	1.26	11
22	Other manufacturing	OMA	0.11	1.41	0.12	1.64	11
23	Scrap and Waste	SWA	0.09	0.48	0.08	0.64	12
24	Repair of fabricated metal products, machinery and equipment	RFM	0.43	1.00	0.10	1.53	15
25	Production and Supply of Electric Power and Heat Power	PSE	1.57	6.81	0.04	8.42	13
26	Production and Distribution of Gas	PDG	0.21	0.38	0.47	1.06	13
27	Production and Distribution of Water	PDW	0.25	1.64	0.06	1.95	13
28	Construction	CON	0.16	1.58	0.11	1.85	14
29	Wholesale and Retail Trades	WRT	0.17	0.41	0.04	0.62	16, 17
30	Transportation, Storage, Posts and Telecommunications	TSP	0.88	1.11	0.16	2.14	19
31	Hotels and Catering Services	HCS	0.33	0.93	0.07	1.33	18
32	Information transmission, software and information technology services	ITS	0.06	0.61	0.04	0.71	20
33	Finance	FIN	0.06	0.30	0.02	0.38	21
34	Real Estate Trade	RET	0.25	0.58	0.02	0.85	21
35	Tenancy and Commercial Services	TCS	0.17	0.53	0.04	0.73	21
36	Scientific research and development, technical services	SRD	0.14	0.75	0.10	0.99	23
37	Water, Environment and Municipal Engineering Conservancy	WEM	0.27	0.88	0.10	1.25	23
38	Resident services, repair and other services	RSR	0.30	0.84	0.07	1.21	24
39	Education	EDU	0.24	0.61	0.05	0.90	23
40	Health care and social works	HSW	0.10	1.20	0.11	1.40	23
41	Culture, Art, Sports and Recreation	CAS	0.13	0.84	0.05	1.02	23
42	Public administration, social security and social organizations	PAS	0.21	0.74	0.06	1.01	22

References

[1] Yu H, Pan S Y, Tang B J, Mi Z F, Zhang Y and Wei Y M 2015 Urban energy consumption and CO_2 emissions in Beijing: current and future *Energy Effic.* **8** 527–43

[2] Meng J, Liu J F, Guo S, Li J S, Li Z and Tao S 2016 Trend and driving forces of Beijing's black carbon emissions from sectoral perspectives *J. Clean. Prod.* **112** 1272–81

[3] Lu W W, Chen C, Su M R, Chen B, Cai Y P and Xing T 2013 Urban energy consumption and related carbon emission estimation: a study at the sector scale *Front. Earth Sci.* **7** 480–6

[4] Mi Z F, Pan S Y, Yu H and Wei Y M 2015 Potential impacts of industrial structure on energy consumption and CO_2 emission: a case study of Beijing *J. Clean. Prod.* **103** 455–i62

[5] Zhang J Y, Zhang Y, Yang Z F, Fath B D and Li S S 2013 Estimation of energy-related carbon emissions in Beijing and factor decomposition analysis *Ecol. Model.* **252** 258–65

[6] Guo S, Liu J B, Shao L, Li J S and An Y R 2012 Energy-dominated local carbon emissions in Beijing 2007: inventory and input–output analysis *Sci. World J.* **2012** 923183

[7] Ge J P and Lei Y L 2014 Carbon emissions from the service sector: an input–output application to Beijing *China Clim. Res.* **60** 13–24

[8] Su B and Ang B W 2014 Input–output analysis of CO_2 emissions embodied in trade: a multi-region model for China *Appl. Energy* **114** 377–84

[9] Zhang B, Qiao H and Chen B 2015 Embodied energy uses by China's four municipalities: a study based on multi-regional input–output model *Ecol. Model.* **318** 138–49

[10] Feng K S *et al* 2013 Outsourcing CO_2 within China *Proc. Natl Acad. Sci. USA* **110** 11654–9
[11] Liu Z *et al* 2016 Targeted opportunities to address the climate-trade dilemma in China *Nat. Clim. Change* **6** 201–6
[12] Zhang B, Qiao H, Chen Z M and Chen B 2015 Growth in embodied energy transfers via China's domestic trade: evidence from multi-regional input–output analysis *Appl. Energy* in press (doi:10.1016/j.apenergy.2015.09.076)
[13] Feng K S, Hubacek K, Sun L X and Liu Z 2014 Consumption-based CO_2 accounting of China's megacities: the case of Beijing, Tianjin, Shanghai and Chongqing *Ecol. Indic.* **47** 26–31
[14] Wang Y, Geschke A and Lenzen M 2015 Constructing a time series of nested multiregion input–output tables *Int. Reg. Sci. Rev.* 0160017615603596
[15] Liu W D, Chen J, Tang Z P, Liu H G, Han D and Li F Y 2012 *Theories and Practice of Constructing China's Interregional Input-Output Tables Between 30 Provinces in 2007* (Beijing: Chinese Statistics Press) (in Chinese)
[16] Guo S and Chen G Q 2013 Multi-scale input–output analysis for multiple responsibility entities: carbon emission by urban economy in Beijing 2007 *J. Environ. Account. Manage.* **1** 43–54
[17] Guo S *et al* 2012 Inventory and input–output analysis of CO_2 emissions by fossil fuel consumption in Beijing 2007 *Ecol. Inf.* **12** 93–100
[18] Chen G Q *et al* 2011 Low-carbon building assessment and multi-scale input–output analysis *Commun. Nonlinear Sci. Numer. Simul.* **16** 583–95
[19] Shao L 2014 Multi-scale input–output analysis of embodied water and its engineering applications *Ph D Thesis* Peking University, Beijing (in Chinese)
[20] Chen G Q, Guo S, Shao L, Li J S and Chen Z M 2013 Three-scale input–output modeling for urban economy: carbon emission by Beijing 2007 *Commun. Nonlinear Sci. Numer. Simul.* **18** 2493–506
[21] Miller R E and Blair P D 2009 *Input-Output Analysis: Foundations and Extensions* 2nd edn (New York: Cambridge University Press)
[22] Guan D *et al* 2014 Determinants of stagnating carbon intensity in China *Nat. Clim. Change* **4** 1017–23
[23] Guan D, Liu Z, Geng Y, Lindner S and Hubacek K 2012 The gigatonne gap in China/'s carbon dioxide inventories *Nat. Clim. Change* **2** 672–5
[24] Liu Z, Geng Y, Lindner S and Guan D 2012 Uncovering China's greenhouse gas emission from regional and sectoral perspectives *Energy* **45** 1059–68
[25] Shan Y, Liu Z and Guan D 2016 CO_2 emissions from China's lime industry *Appl. Energy* **166** 245–52
[26] Mi Z *et al* 2015 Consumption-based emission accounting for Chinese cities *Appl. Energy* in press (doi:10.1016/j.apenergy.2016.06.094)
[27] Beijing Municipal Bureau of Statistics and NBS Survey Office in Beijing 2008 *Beijing Statistical Yearbook 2013* (Beijing: China Statistical Publishing House) (in Chinese)
[28] Shan Y *et al* 2016 New provincial CO_2 emission inventories in China based on apparent energy consumption data and updated emission factors *Appl. Energy* in press (doi:10.1016/j.apenergy.2016.03.073)
[29] China emission accounts and datasets. (http://ceads.net/)
[30] Lenzen M, Kanemoto K, Moran D and Geschke A 2012 Mapping the structure of the world economy *Environ. Sci. Technol.* **46** 8374–81
[31] Lenzen M, Moran D, Kanemoto K and Geschke A 2013 Building eora: a global multi-regional input–output database at high country and sector resolution *Econ. Syst. Res.* **25** 20–49
[32] Su B, Huang H C, Ang B W and Zhou P 2010 Input–output analysis of CO_2 emissions embodied in trade: the effects of sector aggregation *Energy Econ.* **32** 166–75
[33] Su B and Ang B W 2013 Input–output analysis of CO_2 emissions embodied in trade: competitive versus non-competitive imports *Energy Policy* **56** 83–7
[34] Su B and Ang B W 2015 Multiplicative decomposition of aggregate carbon intensity change using input–output analysis *Appl. Energy* **154** 13–20
[35] Wiedmann T, Lenzen M, Turner K and Barrett J 2007 Examining the global environmental impact of regional consumption activities: II. Review of input–output models for the assessment of environmental impacts embodied in trade *Ecol. Econ.* **61** 15–26
[36] Weber C L, Peters G P, Guan D and Hubacek K 2008 The contribution of Chinese exports to climate change *Energy Policy* **36** 3572–7
[37] Feenstra R C and Hanson G H 2004 Intermediaries in entrepôt trade: Hong Kong re-exports of Chinese goods *J. Econ. Manage. Strategy* **13** 3–35
[38] Jin Y 2015 The research on Beijing's imports and exports whose sources and destinations are other economies *Manage. Modernization* 37–9 (in Chinese)
[39] Su B and Ang B W 2011 Multi-region input–output analysis of CO_2 emissions embodied in trade: the feedback effects *Ecol. Econ.* **71** 42–53
[40] Shao L and Chen G Q 2013 Water footprint assessment for wastewater treatment: method, indicator and application *Environ. Sci. Technol.* **47** 7787–94
[41] Chen G Q *et al* 2011 Low-carbon assessment for ecological wastewater treatment by a constructed wetland in Beijing *Ecol. Eng.* **37** 622–8
[42] Shao L and Chen G Q 2016 Embodied water accounting and renewability assessment for ecological wastewater treatment *J. Clean. Prod.* **112** 4628–35
[43] Shao L and Chen G Q 2016 Renewability assessment of a production system: based on embodied energy as emergy *Renew. Sust. Energy Rev.* **57** 380–92
[44] Lenzen M 2011 Aggregation versus disaggregation in input–output analysis of the environment *Econ. Syst. Res.* **23** 73–89
[45] Steen-Olsen K, Owen A, Hertwich E G and Lenzen M 2014 Effects of sector aggregation on CO_2 multipliers in multiregional input–output analyses *Econ. Syst. Res.* **26** 284–302
[46] Su B and Ang B W 2010 Input–output analysis of CO_2 emissions embodied in trade: the effects of spatial aggregation *Ecol. Econ.* **70** 10–8
[47] Andrew R, Peters G P and Lennox J 2009 Approximation and regional aggregation in multi-regional input–output analysis for national carbon footprint accounting *Econ. Syst. Res.* **21** 311–35
[48] Bouwmeester M C and Oosterhaven J 2013 Specification and aggregation errors in environmentally extended input–output models *Environ. Resour. Econ.* **56** 307–35
[49] Lindner S, Legault J and Guan D 2012 Disaggregating input–output models with incomplete information *Econ. Syst. Res.* **24** 329–47
[50] Lindner S, Legault J and Guan D 2013 Disaggregating the electricity sector of China's input–output table for improved environmental life-cycle assessment *Econ. Syst. Res.* **25** 300–20
[51] Lindner S and Guan D 2014 A hybrid-unit energy input–output model to evaluate embodied energy and life cycle emissions for China's economy *J. Ind. Ecol.* **18** 201–11