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Key sectors in carbon footprint responsibility at the city level: a case study of Beijing

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Abstract

Purpose – This paper aims to identify key sectors in carbon footprint responsibility, an introduced concept depicting CO_2 responsibilities allocated through the supply chain containing sectoral activities and interactions. In detail, various key sectors could be identified according to comparative advantages in trade, sectoral linkage and sectoral synergy within the supply chain.

Design/methodology/approach – A semi-closed input–output model is used to make the household income–expenditure relationship endogenous through the supply chain where sectoral CO_2 emissions are calculated, and the production-based responsibility (PR) principle is evaluated. Thus, according to "carbon footprint responsibility", modified hypothetical extraction method is applied to decompose sectoral CO_2 in terms of comparative advantages in trade, sectoral linkage and synergy. Finally, key sectors are identified via sectoral shares and associated decompositions in carbon footprint responsibility.

Findings – Compared to 2005, in 2012, the PR principle failed to track sectoral CO_2 flow, and embodied CO_2 in import and interprovincial export increased, with manufacturing contributing the most; manufacturing should take more carbon responsibilities in the internal linkage, and tertiary sectors in the net forward and backward linkage, with sectors enjoying low carbonization in the mixed linkage; inward net CO_2 flows of manufacturing and service sectors were more complicated than their outward ones in terms of involved sectors and economic drivers; and residential effects on CO_2 emissions of traditional sectors increased, urban effects remained larger than rural ones and manufacturing and tertiary sectors received the largest residential effects.

Originality/value – The value of this paper is as follows: the household income–expenditure relationship got endogenous in intermediate supply and demand, corresponding to the rapid urbanization in megacities; key sectors were observed to change flexibly according to real sectoral activities and interaction; and the

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evaluation of the PR principle was completed ahead of using a certain CO_2 accounting principle at the city level.

Keywords Household, Carbon footprint, Carbon responsibility, Key sector, Modified hypothetical extraction method, Semi-closed input-output model

Paper type Research paper

1. Introduction

Cities have been the main contributors of CO_2 emissions in China (Dhakal, 2009, 2010), the world's largest CO_2 producer since 2007 (Mi *et al.*, 2016). To mitigate CO_2 emissions in practice, the production-based responsibility (PR) principle is fundamental for CO_2 responsibility allocation in China (Liu *et al.*, 2013, 2015). It is acknowledged the PR principle regards the household income – expenditure relationship as an exogenous part separate from the intermediate input-output (IO) system and only considers producers' responsibilities. However, cities, especially megacities, are characterized by rapid urbanization mixed with large rural–urban disparities (Wang and Yang, 2016, Wang *et al.*, 2012) and the income–expenditure relationship (Li *et al.*, 2015b, Wang *et al.*, 2012), allowing households and sectors to interact closely to satisfy intermediate supply and demand. Furthermore, city-level economy has complex cross-boundary interactions such as monetary, commodity, resource and population flows, so associated CO_2 emissions correspondingly flow (Guo *et al.*, 2012, Wang *et al.*, 2014a, Feng *et al.*, 2014, Mi *et al.*, 2016) according to sectoral activities and interactions such as production and round-about production process (Zhao *et al.*, 2016, 2015, Wang *et al.*, 2013b). Consequently, the PR principle probably distorts sectoral CO_2 responsibilities where three puzzles face cities' sustainability:

(1) How to make the household income–expenditure relation endogenous through the supply chain?

(2) How to determine carbon responsibilities?

(3) How to identify key sectors based on (1) and (2)?

Referring to the puzzle (1), the semi-closed IO model could make sense (Chen *et al.*, 2015). It was pioneered by Batey *et al.* (1987) and is usually applied for households. In detail, it allows the household consumption column and the income row to be placed into the intermediate IO system, and then observes the changes in household consumption caused by a change in labor input because of increased output. In other words, although the traditional IO model is a powerful tool to measure residential impacts on CO_2 (Zhang *et al.*, 2015a, Wang and Yang, 2016, Feng *et al.*, 2013), unlike the semi-closed IO model, it ignores endogenous effects of residential income–expenditure relationship on the intermediate supply and demand.

Concerning the puzzle (2), a concept "carbon footprint responsibility" is proposed, referring to allocation of the CO_2 responsibility along the supply chain containing both sectoral activities and interactions within and outside a city's territorial boundary. Previous studies think of sectors to shoulder different responsibilities (Zhang, 2013, Marques *et al.*, 2012, Bastianoni *et al.*, 2004), such as PR, consumer-based responsibility (CR), income-based responsibility (IR) and shared responsibility (SR). Among these responsibilities, PR (causing carbon leakage issue), CR and IR disregard the responsibilities shared among producers, consumers and income recipients, and SR has difficulties in finding suitable weights for allocation, despite its advantages in shared responsibilities. Under such a circumstance, carbon footprint, referring to accumulated emissions generated from a supply chain or the life cycle of a product (Hertwich and Peters, 2009), provides an outlet to evaluate responsibilities through a supply chain or a whole life cycle.

Regarding puzzle (3), key sectors were pioneered by Rasmussen (1956) and represent the sectors with the largest potential to spread growth impulses throughout the economy, which could be identified based on the semi-closed IO model integrated with modified hypothetical extraction method (HEM). As explained in "carbon footprint responsibility", determining sectors' responsibilities needs details of sectoral activities and interactions within and outside the territorial boundary: First, comparative advantages in trade affect key sector identification significantly (Cadarso *et al.*, 2012), but related studies are limited for Chinese cities (Chen *et al.*, 2013, Meng *et al.*, 2016, Chen *et al.*, 2016b, 2016a). Second, it is useful to know sectoral linkages when tracing sectoral CO_2 flows and adopting CO_2 migration policy (Strassert, 1968, Schultz, 1977, Ali, 2015, Wang *et al.*, 2013b, Zhao *et al.*, 2016) using sensitivity analysis (Tarancon and Del Rio, 2007) and HEM (Cella, 1984). However, previous studies lack further exploration of interlinkages among sectors (Tarancon and Del Rio, 2007) and mainly focus on the national level (Zhao *et al.*, 2016, Wang *et al.*, 2013b). In this regard, modified HEM not only details sectoral CO_2 linkage combining effects from technology, structure and final demand, but also elaborates the inward and outward flows between sectors (Duarte *et al.*, 2002). Third, sectoral synergy for CO_2 reduction is in need of more comprehensive exploration into sectoral linkage (Wang *et al.*, 2013b, Zhao *et al.*, 2016, 2015). It is because sectoral synergy enveloping from sectoral linkage allows producer service industry to optimize and integrate the production and sale process by investing knowledge, information technology, human capital and management strategies (Gebauer, 2008, Ciriaci and Palma, 2016, Castellacci, 2008, Guerrieri and Meliciani, 2005), prompting the innovation capacity and economic efficiency of the whole sectoral network (Coffey and Bailly, 1992, O'Farrell and Hitchens, 1990, MacPherson, 1997) and then making service-oriented economy more probable to develop the low-carbon economy (Yuan *et al.*, 2016).

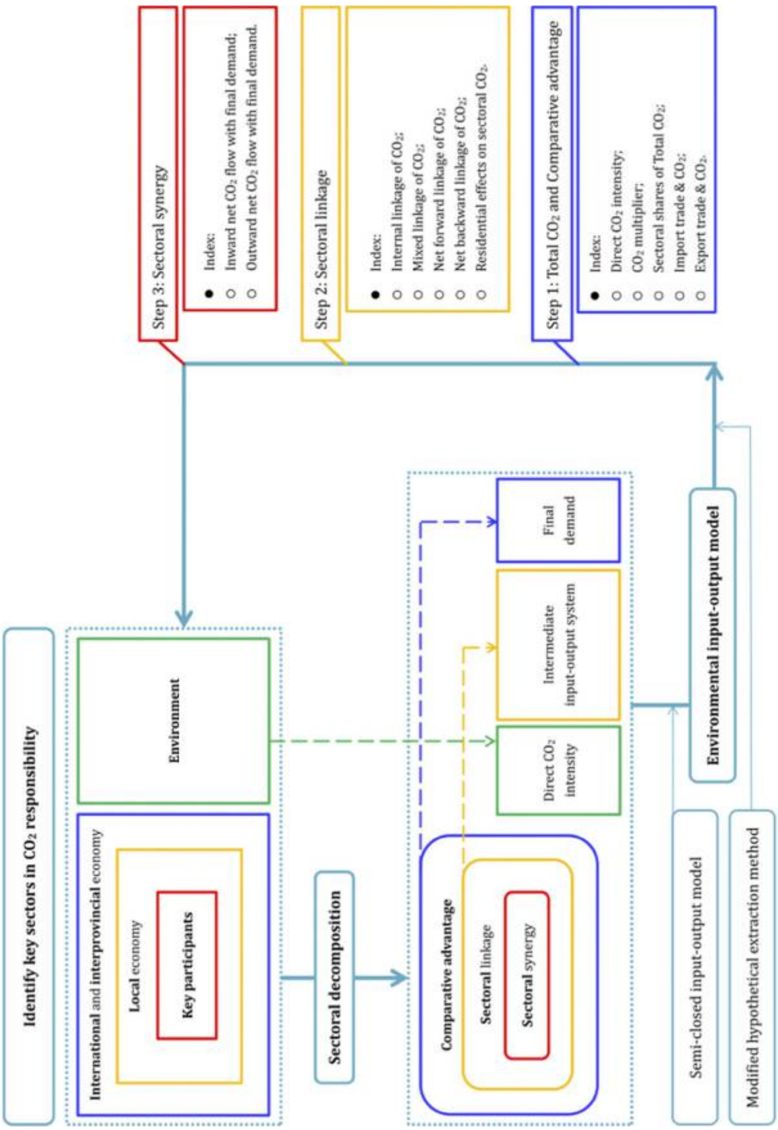
Beijing, the capital of China, has been explored widely in CO_2 reduction, owing to its unique economic status and serious air pollution (Zhang *et al.*, 2015b); increasing urban population, more energy consumption and industrial structure transform lacking R&D development (Wang *et al.*, 2012); accelerated changes in technology, lifestyle and societal transformation (Feng *et al.*, 2013); good data availability (Wang *et al.*, 2013a); and its useful experience and lessons in industrial restructuring and greenhouse gas mitigation for cities within and outside Beijing (Wang, 2008, Li *et al.*, 2015a, Hu *et al.*, 2017). Additionally, because of the similarities in CO_2 accounting principle (i.e. PR principle) and compilation principle of IO tables possessed by 30 key Chinese provinces or cities, it could be useful for these cities to rediscover key sectors in carbon footprint responsibility by using the methods proposed in this paper.

Therefore, to identify key sectors in carbon footprint responsibility, this paper took Beijing in 2005 and 2012 as an example, using the semi-closed IO model integrated with modified HEM. The remainder of the paper is organized as follows: Section 2 introduces method and data, Section 3 analyzes and discusses results and Section 4 performs conclusions, policy implications and future studies.

2. Model and data

2.1 Research framework

A semi-closed IO model is used to make the household income–expenditure relationship endogenous through the supply chain where sectoral CO_2 emissions are calculated and the PR principle is evaluated. Thus, followed by the concept called "carbon footprint responsibility", we applied modified HEM to decompose sectoral CO_2 in terms of comparative advantages in trade, sectoral linkage and synergy, measuring sectoral CO_2 caused by sectoral activities and interactions (Figure 1). Finally, after ranking all the results based on the first two steps, key sectors could be identified in carbon footprint responsibility.



Note: Sectors studied include traditional sectors ranging from Sector 1 to Sector 17 and residential sectors involving S18 (rural household) and S19 (urban household). Related sectoral classifications could be found in Tables AI and AII in the Appendix

Figure 1.
Framework for sectoral performances and associated CO_2 emissions

2.2 Sectoral CO_2 emissions: semi-closed input–output model

Based on the semi-closed IO model, we first examined whether the PR principle could reflect the real origins of CO_2 emissions, by establishing some indexes including direct CO_2 intensity, CO_2 multiplier, total CO_2 emission factors and sectoral CO_2; thus, we could identify the first category of key sectors according to sectoral CO_2 emissions generated by the comparative advantages in trade.

2.2.1 Evaluation of the PR principle with four indexes. The basic traditional IO model is:

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

$$Y = H + G + CA + EX - IM \tag{2}$$

where X is a vector of the total output with element of sector j, x_j; A is the technological coefficient matrix with element a_{ij} representing the requirement of sector i for producing per unit of output of sector j; $(I-A)^{-1}$ is the Leontief inverse matrix; and Y is the final demand of sector j, including household consumption H, government consumption G, capital formation CA and net export $(EX - IM)$.

Based on the above traditional IO model, there are four steps explaining how to gain the semi-closed IO model for the studied area whose IOT is competitive.

2.2.1.1 Changing competitive IOT into non-competitive IOT. Followed by the basic structure of semi-closed IO model in Miyazawa (1976), import is not included in the intermediate IO system, which is also a crucial point distinguishing competitive and non-competitive IOT in China (Su and Ang, 2013), because competitive IOT does not distinguish origins of products in the intermediate IO system. Therefore, the imports should be deducted from each element except the export in IOT in the following formula (Chen *et al.*, 2015) when considering Beijing's IOT is competitive:

$$\varphi_i = (x_i - e_i)/(x_i + m_i - e_i) \tag{3}$$

where φ_i is the proportion of domestic product to the total domestic demand of sector i, x_i is the total output of sector i, m_i is the import of sector i and e_i is the export of sector i. Thus, we multiply each supply row of sector i in IOT by φ_i, gaining the domestic products delivered to industries and final demand categories excluding the export.

2.2.1.2 Changing the technological coefficient matrix.

$$A^* = \begin{bmatrix} A & H^{con} \\ H^{inc} & 0 \end{bmatrix} \tag{4}$$

where A^* is the technological coefficient matrix of the semi-closed IO model, H^{con} is the vector of household consumption coefficient (i.e. the ratio of household consumption of each sector to total output of this sector) and H^{inc} is the row vector of household income coefficient (i.e. the ratio of the income of a certain household for each sector to total household income).

2.2.1.3 Changing the final demand.

$$Y^* = G + CA + (EX - IM) \tag{5}$$

where Y^* is the final demand of the semi-closed IO model without household consumption, compared to Y in formula (2).

2.2.1.4 Obtaining the total output vector.

$$X^* = (I - A^*)^{-1} Y^* \tag{6}$$

where X^* is the total output vector of the semi-closed IO model.

Owing to the data availability concerning energy consumption at sector level in Beijing, energy-related CO_2 is:

$$C_i = W \cdot EF \cdot 44/12 \tag{7}$$

$$C = e(I - A^*)^{-1} Y^* \tag{8}$$

where C_i is the energy-related CO_2 of sector i, W is energy consumption (ton of standard coal equivalent, tce) and EF is the CO_2 emission factor of energy consumption (t/tce). The value of EF is recommended as 0.67 according to Energy Research Institute National Development and Reform Commission, the factor 44/12 is the ratio of molecular weights of CO_2 to C, e is the diagonal matrix of direct CO_2 intensity (i.e. the ratio of CO_2 emissions of sector i, C_i, to the total output sector i, x_i) and C is the vector of CO_2 emissions based on the semi-closed IO model.

Therefore, four indexes evaluating the PR principle are:

(1) Index 1, the direct CO_2 intensity referring to the direct CO_2 emissions caused by per unit of total output;
(2) Index 2, the CO_2 multiplier that is the indirect CO_2 caused by per unit of total output based on the ratio of total CO_2 intensity (i.e. Index 3) to direct CO_2 intensity;
(3) Index 3, the total CO_2 emission factor which equals $e(I - A^*)^{-1}$; and
(4) Index 4, referring to sectoral CO_2 based on semi-closed IO model.

Additionally, when comparing index 1, 2 and 3 in 2005 and 2012, total output in Beijing's IOT is at current price. So, total output in 2012 is supposed to be converted to 2005 constant price to be in harmony with that in 2005:

$$GPI_i^{2012} = \left(GPI_i^{2005}\right)^6 / \left(GPI_i^{2006}\right)\left(GPI_i^{2007}\right)\left(GPI_i^{2008}\right)\left(GPI_i^{2009}\right)\left(GPI_i^{2010}\right)\left(GPI_i^{2011}\right) \tag{9}$$

$$GRP_i^{2012} = GRP_i^{2005} \times GPI_i^{2012} \tag{10}$$

where GPI_i^t is the gross regional product price index at sector level in a certain year t for the sector i, and GRP_i^t is the gross regional product at sector level in year t for sector i.

2.2.2 Key sectors according to CO_2 caused by comparative advantages. CO_2 emissions driven by comparative advantages in trade could fall into two categories: CO_2 caused by import and export within and outside an area.

First, CO_2 emissions driven by import are:

$$e^{total} = e\left[(I - A^*)^{-1} - I\right] \tag{11}$$

where e^{total} is the modified CO_2 consumption coefficient, detected from imports using formula (3) to reflect the influence of import on city-level CO_2 caused by per unit of output.

Thus, CO_2 emissions driven by export are:

$$C^{ei} = e(I - A^*)^{-1} EX^{ei} \tag{12}$$

$$C^{eo} = e(I - A^*)^{-1} EX^{eo} \tag{13}$$

where C^{ei} represents the CO_2 caused by Beijing's interprovincial export, EX^{ei} means the vector of Beijing' interprovincial export, C^{eo} is the CO_2 induced by its international export and EX^{eo} is the vector of Beijing's international export.

2.3 Sectoral linkage, synergy and CO_2: modified hypothetical extraction method

2.3.1 Key sectors according to CO_2 caused by sectoral linkage. HEM is used to measure the significance of one sector on the whole economy by comparing the real economic system where the sector is not extracted with the hypothetical economic system where the sector is extracted, generating forward and backward sectoral linkages. Moreover, modified HEM could further break down the sectoral linkages into four components, namely, internal linkage (*IL*), mixed linkage (*ML*), net forward linkage (*NFL*) and net backward linkage (*NBL*), identifying the associated key sectors in CO_2 reduction.

The sectoral system of the city, Q, is divided into two sectoral clusters, Q_s and Q_{-s}. Q_s represents the sectoral cluster with sectors of same characteristics, and Q_{-s} the cluster with the remaining sectors. And then, the total sectors of the city can be classified:

$$Q = \begin{bmatrix} Q_{s,s} & Q_{s,-s} \\ Q_{-s,s} & Q_{-s,-s} \end{bmatrix} \tag{14}$$

And then, the calculation of sectoral CO_2 based on the semi-closed IO model is:

$$\begin{bmatrix} C_s \\ C_{-s} \end{bmatrix} = \begin{bmatrix} e_s & 0 \\ 0 & e_{-s} \end{bmatrix} \left(\begin{bmatrix} A^*{}_{s,s} & A^*{}_{s,-s} \\ A^*{}_{-s,s} & A^*{}_{-s,-s} \end{bmatrix} \begin{bmatrix} X_s \\ X_{-s} \end{bmatrix} + \begin{bmatrix} Y^*{}_S \\ Y^*{}_{-S} \end{bmatrix} \right) \tag{15}$$

$$\begin{bmatrix} C_s \\ C_{-s} \end{bmatrix} = \begin{bmatrix} e_s & 0 \\ 0 & e_{-s} \end{bmatrix} \left(\begin{bmatrix} B_{s,s} & B_{s,-s} \\ B_{-s,s} & B_{-s,-s} \end{bmatrix} \begin{bmatrix} Y^*{}_S \\ Y^*{}_{-S} \end{bmatrix} \right) \tag{16}$$

where $\begin{bmatrix} C_s \\ C_{-s} \end{bmatrix}$ is the total CO_2 emissions vector, $\begin{bmatrix} e_s & 0 \\ 0 & e_{-s} \end{bmatrix}$ is the diagonal matrix of direct emission intensity, $\begin{bmatrix} X_s \\ X_{-s} \end{bmatrix}$ is the total output vector, $\begin{bmatrix} A^*{}_{s,s} & A^*{}_{s,-s} \\ A^*{}_{-s,s} & A^*{}_{-s,-s} \end{bmatrix}$ is the technological coefficient matrix and $(I - A)^{-1} = \begin{bmatrix} B_{s,s} & B_{s,-s} \\ B_{-s,s} & B_{-s,-s} \end{bmatrix}$ is the Leontief inverse matrix.

The CO_2 emissions generated by the sectoral system when the sector s is extracted are:

$$\begin{bmatrix} C_s \\ C_{-s} \end{bmatrix} = \begin{bmatrix} e_s & 0 \\ 0 & e_{-s} \end{bmatrix} \begin{bmatrix} \left(I - A^*_{s,s}\right)^{-1} & 0 \\ 0 & \left(I - A^*_{-s,-s}\right)^{-1} \end{bmatrix} \begin{bmatrix} Y^*_S \\ Y^*_{-S} \end{bmatrix} \tag{17}$$

The difference between the sectoral CO_2 when the sector s is not extracted, C^{bef}, and those when the sector s is extracted, C^{aft}, is:

$$C^{bef} - C^{aft} = \begin{bmatrix} e_s & 0 \\ 0 & e_{-s} \end{bmatrix} \begin{bmatrix} C^{bef}_s - C^{aft}_s \\ C^{bef}_{-s} - C^{aft}_{-s} \end{bmatrix} \tag{18}$$

$$C^{bef} - C^{aft} = \begin{bmatrix} B_{s,s} - \left(I - A^*_{s,s}\right)^{-1} & B_{s,-s} \\ B_{-s,s} & B_{-s,-s} - \left(I - A^*_{-s,-s}\right)^{-1} \end{bmatrix} \begin{bmatrix} Y^*_s \\ Y^*_{-s} \end{bmatrix} \tag{19}$$

Four elements of sectoral linkages after decomposing the formula (19) are:

$$IL = u'_s e_s \left(I - A^*_{s,s}\right)^{-1} Y^*_s \tag{20}$$

$$ML = u'_s e_s \left[B_{s,s} - \left(I - A^*_{s,s}\right)^{-1}\right] Y^*_s \tag{21}$$

$$NFL = u'_s e_s B_{s,-s} Y^*_{-s} \tag{22}$$

$$NBL = u'_{-s} e_{-s} B_{-s,s} Y^*_s \tag{23}$$

where *IL* is the CO_2 generated by the products and service created by Q_s itself to satisfy its own final demand. *ML* is the CO_2 generated by the products and service created by Q_s originally but then produced by other sector (cluster), Q_{-s}, and finally repurchased and reproduced by Q_s, aiming at meeting the final demand of Q_s. To meet the final demand of other sector (cluster) Q_{-s}, Y^*_{-s}, there would be CO_2 (*NFL*) generated during the direct production and indirect production of Q_s. To satisfy the final demand of Q_s, Y^*_s, there would be CO_2 (*NBL*) generated during the direct and indirect production of another sector (cluster), Q_{-s}. $u'_s = (1, 1 \ldots 1)$ is the unit vector for sector s and $u'_{-s} = (1, 1 \ldots 1)$ is the unit vector for sector $-s$.

2.3.2 Key sectors according to CO_2 caused by sectoral synergy. With *NFL* and *NBL*, we cannot figure out sources, destinations and economic drivers of inward and outward CO_2 between sectors. So, we further decomposed *NFL* and *NBL* and then got the inward and outward net CO_2 flow of each sector, respectively, identifying the corresponding key sectors. In addition, economic drivers behind the above CO_2 flows could be to explore the consumption pattern of key sectors.

Inward net CO_2 flow for each sector is obtained from the decomposition of *NFL* of Q_s, and Q_{-s} consists of all the sectors but sector s. In this regard, *NFL* of Q_s could be regarded as the sum of CO_2 caused by sector s to meet the demands of sector t in Q_{-s}:

$$NFL = NFL_{s \to t} = u'_s e_s B_{s,t} Y^*_t \in (-s) \tag{24}$$

Outward CO_2 flow for each sector could be obtained from the decomposition of *NBL* of *Qs*.

NBL of Q_s could be considered as the sum of CO_2 caused by each sector as a member of Q_{-s}, for example, sector *t* to satisfy the needs of sector *s*:

$$NBL = NBL_{t \to s} = u_t^{'} e_t B_{t,s} Y_s^* t \in (-s) \quad (25)$$

2.5 Data source and processing

The data of the IO tables origin from Beijing IO Table MMV and 2012 (BMBS, 2006a; 2013a), and other data come from Beijing Statistical Yearbook 2005 and 2012 (BMBS, 2006b; 2013b). Data processing can be undertaken as follows:

- removing the household consumption column and household income row into the intermediate IO system (Figure A1 in the Appendix);
- classifying the 42 sectors of IOT and the 57 sectors consuming energy into 17 traditional sectors, urban and rural households according to Industrial Classification for Economic Activities in China (Table AI and Table AII in the Appendix); and
- changing competitive IOT into non-competitive IOT based on the formula (3) to meet the requirements of the semi-closed IO model.

3. Result analysis and discussion

3.1 The PR principle, comparative advantage and key sectors

3.1.1 Indexes for evaluating the PR principle. Figure 2 shows that the sectoral shares of direct CO_2 intensity, CO_2 multiplier, total CO_2 emission factor and total CO_2 emissions were different from one another. In detail, CO_2 reduction measures should be implemented to mining (S2), hotels (S7) and other services (S11) under the PR principle [Figure 2(a)]. When considering indirect CO_2 per unit of output, finance (S9), tendency services (S15) and urban household (S19) should be provided with strict CO_2 mitigation actions [Figure 2(b)]. But if economic drivers are also taken into account, manufacturing (S3), transportation (S14) and urban household (S19) could be in the greatest need of CO_2 alleviation [Figure 2(d)], while energy (S4), RE trade (S10), transportation (S14) and urban household (S19) could be given top priorities for CO_2 reduction without thinking of economic drivers [Figure 2(c)].

3.1.2 Comparative advantages in carbon footprint responsibility. Figure 3(a) and (b) shows imports in Beijing continued exerting positive but not enough effects on sectoral CO_2 reduction, while its interprovincial export generated the most CO_2 emission compared to other final demand categories. From a sector perspective, for manufacturing (S3), each sector reduced CO_2 due to the impacts of maufacturing's import, while the import of agriculture (S1), WR trade (S6) and transportation (S14) did not prompt its own low-carbon development. Besides, in 2012, manufacturing (S3) witnessed an increasing trend in its largest contribution to CO_2 emissions driven by interprovincial export [Figure 3(c) and (d)].

3.1.3 Discussion. The PR principle could not comprehensively reflect real origins of CO_2 emissions according to the four indexes mentioned in Section 3.1.1. Results represent obvious differences in CO_2 flows under different accounting principles, distinct from previous studies highlighting the application of some principles such as the PR or the CR principle (Wei *et al.*, 2016, Shan *et al.*, 2016), instead of explaining why to choose these principles.

Compared to the modified CO_2 consumption coefficients and CO_2 embodied in interprovincial and international trade used in the paper, Feng *et al.* (2014) and

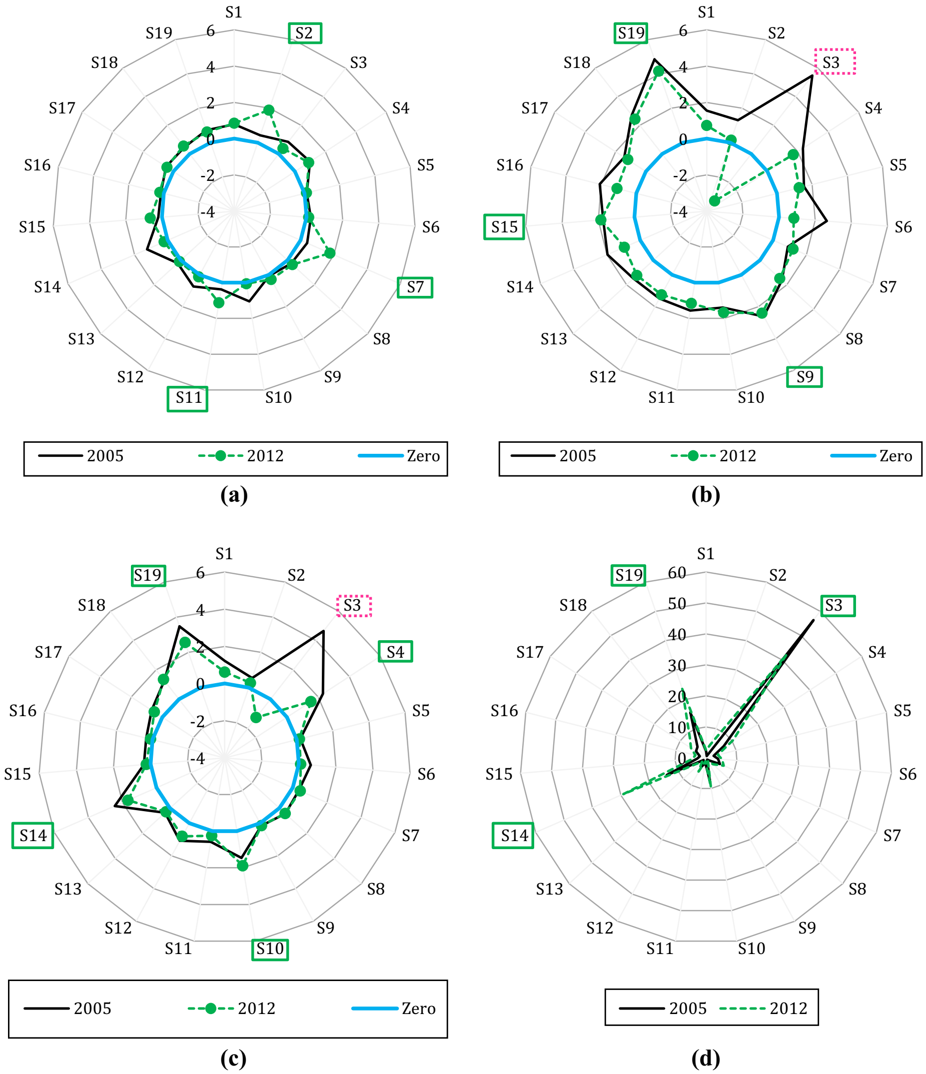
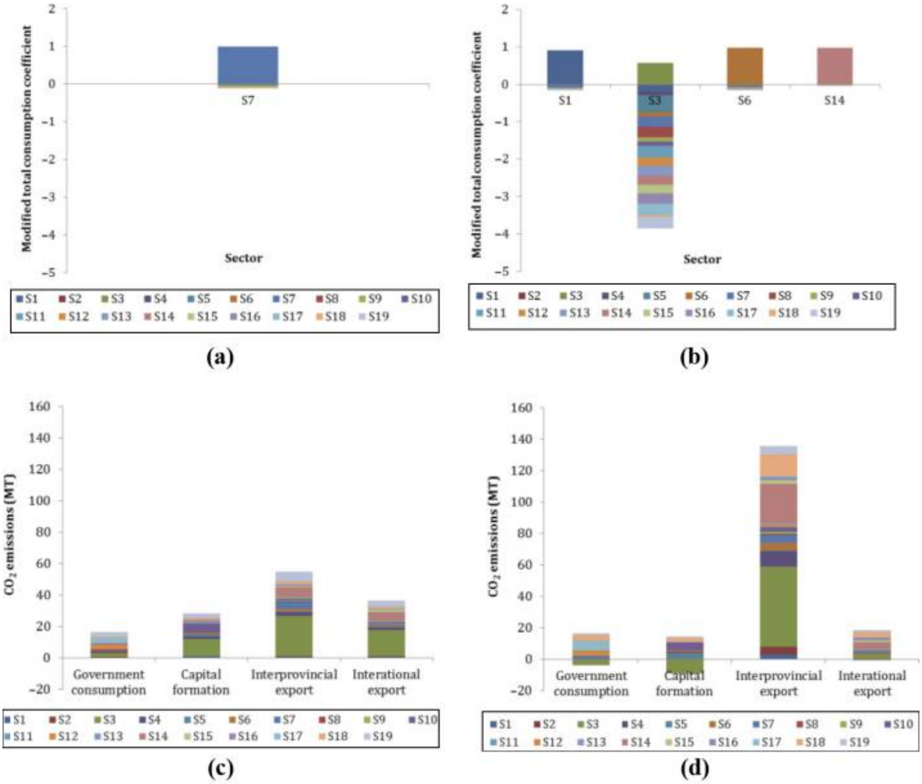


Figure 2.
Indexes for evaluating the PR principle

Notes: (a) Direct CO_2 intensity; (b) CO_2 multiplier; (c) total CO_2 emission factor; and (d) total CO_2 emissions

Chen *et al.* (2013) have assessed sectoral CO_2 caused by interprovincial trade and have obtained sectoral CO_2 intensity induced by international and interprovincial trade. They all shifted their attention away from decomposing embodied CO_2 emissions or intensity between sectors.

Besides, it is the Beijing's trade condition that affects a lot why trade either promotes less intensive CO_2 accumulation or reduces CO_2 emissions on a smaller scale than expected.



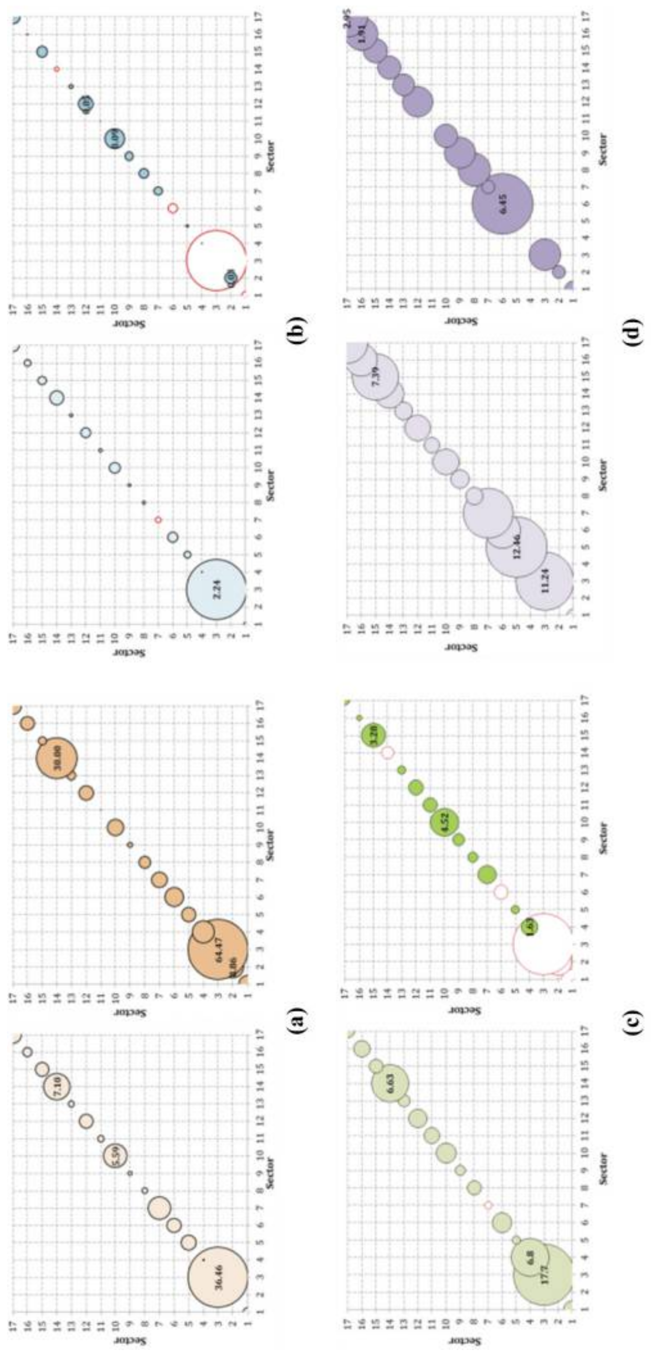
Notes: (a) Import and CO_2 emissions in 2005; (b) import and CO_2 emissions in 2012; (c) export and CO_2 emissions in 2005; and (d) export and CO_2 emissions in 2012

Figure 3. Sectoral CO_2 caused by comparative advantages in trade in Beijing in 2005 and 2012

Beijing is recognized as the import-dependent city with its export deficit of \$1.22bn in 1983 and \$210.08bn in 2015 (BMBS, 2016). As an important entrepot trade city, it imports many raw materials and core components arising from the upstream of manufacturing from Japan, the USA and Europe; after processing and assembling these products, it exports them both domestically and abroad. So its trade and associated CO_2 reduction could not achieve the long-term healthy development easily with more dependence on raw materials instead of advanced technologies, more intractable given the insufficiency in in-house high-tech improvements (Guan *et al.*, 2005, BMBS, 2010).

3.2 Sectoral linkage and key sectors

3.2.1 Key sectors selected according to sectoral linkage. Figure 4(a) shows that in Beijing in 2012, among all sectors, manufacturing (S3) and transportation (S14) continued generating the largest internal CO_2 linkage, of which their interprovincial export accounted for the largest proportion (about 61 per cent and 25 per cent, respectively). That is because along with fewer barriers in interprovincial trade than those in international trade, manufacturing



Notes: White bubbles with red margin correspond to negative CO_2 linkage; (a) IL in 2005 and 2012; (b) ML in 2005 and 2012; (c) NFL in 2005 and 2012; and (d) NBL in 2005 and 2012

Figure 4.
CO_2 linkages of traditional sectors in Beijing in 2005 and 2012 (unit: $MtCO_2e$)

is vital to the secondary industry in Beijing. Meanwhile, energy intensity and population size have played an increasing crucial role in transportation (Wei *et al.*, 2016).

Figure 4(b) depicts there was a downward trend in sectoral mixed linkages, indicating it was lower carbon-intensive in 2012. Especially, in 2005, only manufacturing (S3) had had a largest mixed linkage, but in 2012, S3 became the sector with the smallest mixed linkage, with mining (S2), RE activities (S10) and education (S12) being top 3 sectors. Figure 4(c) illustrates tertairy sectors were more carbon-intensive in NFL in 2012 than secondary and primary sectors. Expecially, RE activities (S10), tendency services (S15) and hotels (S7) were top 3 sectors in 2012, when manufacturing (S3) was characterized obviously by its negative NFL. Figure 4(d) presents the distribution of NBL was the same as that of the NFL in 2012. Particularly, wholesale and retail trade (S6), public service (S17) and manufacturing (S3) were the top 3 sectors, while construction (S5) had the largest negative NBL.

3.2.2 Discussion. According to varied sectoral CO_2 linkages, CO_2 flows were flexible due to diverse distributions through the supply chain so that producers could not be the only focus on CO_2 reduction. Nonetheless, CO_2 mitigation policies in Beijing hinge on the PR principle, controlling CO_2 by end-of-pipe treatment in energy-intensive sectors, such as manufacturing, and production and supply of electricity, gas and water, rather than tracking the real origin of CO_2 emissions and measuring household effects (Beijing Government, 2013; 2016a, Yuan *et al.*, 2016). Simultaneously, more studies explored the impacts of industry structure or a certain sector on city-level CO_2 reduction in the context of economic development and livable environment in Beijing (Creutzig and He, 2009, Wang *et al.*, 2014b, Yu *et al.*, 2015a, 2015b, Mi *et al.*, 2015), needing future attention on the impacts of inter-sectoral coordination (Xia *et al.*, 2015, Tian *et al.*, 2013). Just as Zhang *et al.* (2015b), merely considering CO_2 reduction in energy-intensive sectors could result in inefficient technology development and finally increase the marginal costs.

Additionally, in Beijing, service sectors occupied 79.79 per cent of total GDP in 2015 (BMBS, 2016), turning out more carbon-intensive than secondary and primary sectors. In line with Wei *et al.* (2016), Tian *et al.* (2013) and Wang *et al.* (2012), results show that consumption patterns of service sectors increase CO_2, because materials provided per unit of output of service sectors were used inefficiently.

3.3 Sectoral synergy and key sectors

According to 3.2, *NFL* and *NBL* were more complicated due to their high accumulation in a set of service sectors. Not only has the CO_2 reduction potential of sectoral synergy between producer service sectors and traditional sectors been emphasized in policies or regulations (Beijing Government, 2011; 2016a), but also academic requirements for inter-sector cooperation are advocated (Renukappa *et al.*, 2013). However, related studies lacked detailed impacts of sectoral synergy on CO_2 (Zheng *et al.*, 2012, Creutzig and He, 2009, Wang *et al.*, 2014b, Yuan *et al.*, 2016). Meanwhile, a discussion over how to reduce CO_2 emissions via sectoral synergy was promoted, highlighting the significance of combining key sectors with associated factors such as socioeconomic, energy-related and economy-related factors, as well as socio-political acceptability (Zhang *et al.*, 2015b, Rosen, 2009). Therefore, *NFL*, *NBL* and related economic drivers behind were decomposed to select the corresponding key sectors.

3.3.1 Inward net CO_2 flow of selected key sectors. Based on *NFL* in 2012, hotels (S7), RE activities (S10) and tendency services (S15) were selected as the main contributors to total *NFL*. In addition, manufacturing (S3) has obviously decreased its NFL, instructing how to reduce CO_2 emissions caused by this sectoral linkage.

Figure 5(a) illustrates most inward CO_2 flows of S7 were driven by the demands from manufacturing (S3), transportation (S14), technical services (S16) and public services (S17). Concerning economic drivers behind S7's flows, Beijing's interprovincial trade of S3 and S16 contributed the most, while government consumption of S14 and S17 made the main contributions.

Figure 5(b) describes inward flows of RE activities (S10) were mostly caused by the consumption from manufacturing (S3), WR trade (S6), IT (S8), finance (S9), technical services (S16) and public services (S17). Furthermore, Beijing's interprovincial trade of S3, S6, S8 and S16 contributed more to the inward CO_2 flow of S10 than their other final demands, so did S9's capital formation and S17's government consumption.

Figure 5(c) shows the inward CO_2 flows of tendency services (S15) were mainly induced by the consumption from manufacturing (S3), WR trade (S6) and public services (S17). The interprovincial export regarding S3 and S6 was the largest contributor, as well as the government consumption regarding S17.

Figure 5(d) shows that the consumption of construction (S5), WR trade (S6), IT (S8), leisure (S13), transportation (S14), technical services (S16) and public services (S17) caused the most negative inward flows of manufacturing (S3). More importantly, the import-impacted interprovincial export of S6, S8 and S16 contributed more than their other final demands. Likewise, international export of S13, capital formation of S5 and government consumption of S14 and S17 were all dependent on import and accounted for the larger proportion of S3's contributions than their other final demands.

3.3.2 Outward net CO_2 flow of selected key sectors. According to *NBL* in 2012, manufacturing (S3), WR trade (S6) and public services (S17) were selected as the main contributors. Additionally, construction (S5) had decreased *NBL*, guiding other sectors how to reduce *NBL*.

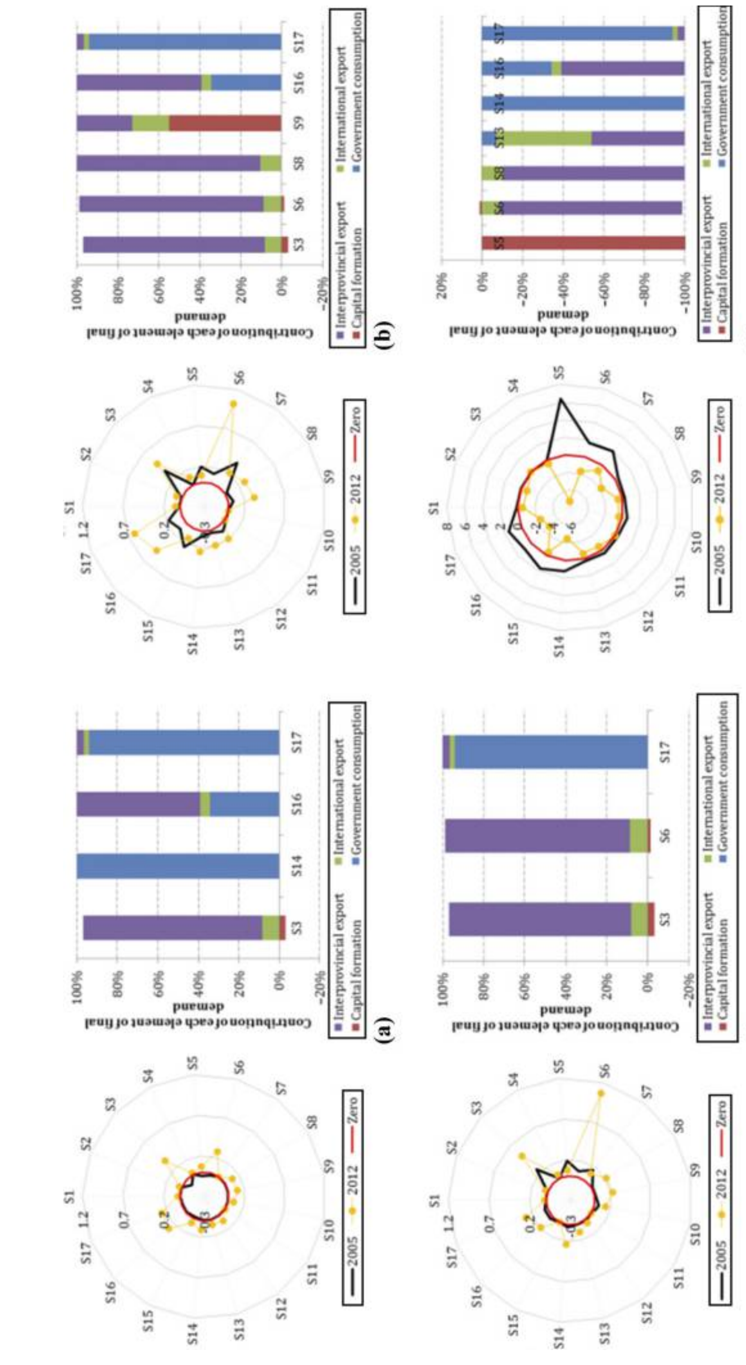
Figure 6(a) shows the positive outward CO_2 flows of manufacturing (S3) were from the productions of energy (S4) and tenancy services (S15). But its negative outward flow resulted from the production of agriculture (S1), mining (S2), WR trade (S6) and hotels (S7). Besides, S3's interprovincial export contributed more to its outward flows than its other final demands.

Figure 6(b) illustrates that the positive outward CO_2 flows of WR trade (S6) came from productions of RE trade (S10) and tenancy services (S15); however, its negative CO_2 flows from the production of manufacturing (S3). Regarding economic drivers for WR trade (S6), its interprovincial import contributed more than its other final demands.

Figure 6(c) depicts the positive outward CO_2 flows of public services (S17) were mainly from the production of RE activities (S10), while the production of manufacturing (S3) primarily affected S17's negative flows. Meanwhile, S17's interprovincial export contributed the most.

Figure 6(d) shows that the negative outward CO_2 flows of construction (S5) mostly stemmed from the production of manufacturing (S3), when comparing to its positive outward ones mainly coming from the production of manufacturing (S3) in 2005. Besides, the capital formation of S5 contributed more for this change in its outward CO_2 flow than its other final demands.

3.3.3 Discussion. In general, the largest CO_2 flows formed between manufacturing and service sectors, and between service sectors in Beijing in 2012. This result indicates that the consumption patterns of manufacturing and service sectors were more carbon-intensive through their sectoral interactions, i.e. sectoral synergy. Despite Beijing's achievements in the post-industrial development stage, CO_2 control will not go smoothly without the following problems being handled (Beijing Government, 2016b):



Notes: (a) Hotels; (b) RE activities; (c) tendency services; and (d) manufacturing; the pictures on the left sides of Figure 5 (a), (b), (c) and (d) represent the CO_2 flows and those on the right sides of Figure 5 (a), (b), (c) and (d) correspond to the associated economic drivers

Figure 5.
Inward net CO_2 flows of hotels, RE activities, tendency services and manufacturing with related economic drivers for each selected sector (unit: $MtCO_2e$)

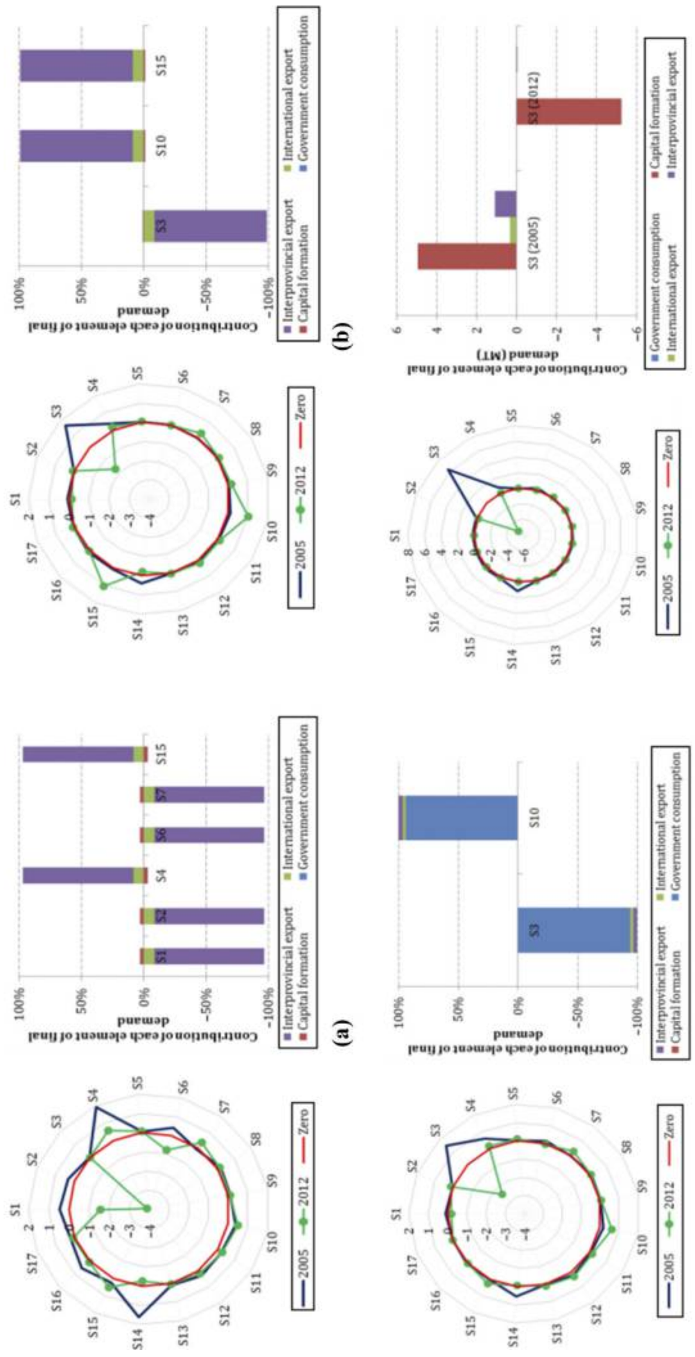


Figure 6.
Outward net CO_2 flow of manufacturing, WR trade, public services and construction with related economic drivers for each selected sector (unit: $MtCO_2e$)

Notes: (a) Manufacturing; (b) WR trade; (c) public services; and (d) construction; the pictures on the left sides of Figure 6 (a), (b), (c) and (d) represent the CO_2 flows and those on the right sides of Figure 6 (a), (b), (c) and (d) correspond to the associated economic drivers

- the modest expansion of manufacturing accesses advanced technology and management insufficiently, making it hard to improve the overall CO_2 reduction potential of secondary industry; and
- service industry itself also face severe problems, such as rural–urban disparity caused by the unbalanced configuration (Zhang *et al.*, 2014), limited spillover effects due to the resemblance to orientation among sectors, deficient excellent proprietary intellectual property rights and professional high-end talents, unimproved systematic marketing mechanism (Zheng *et al.*, 2012) lacking coordination between producer service sectors and manufacturing (Qiu *et al.*, 2008) and increasing energy use of service industry to challenge future CO_2 control (Beijing Government, 2016a).

To address these problems, results show outward net CO_2 flows induced by the above-mentioned sectoral interactions were easier to control than inward ones because the latter flows were more complex than the former ones in terms of interacted sectors and economic drivers.

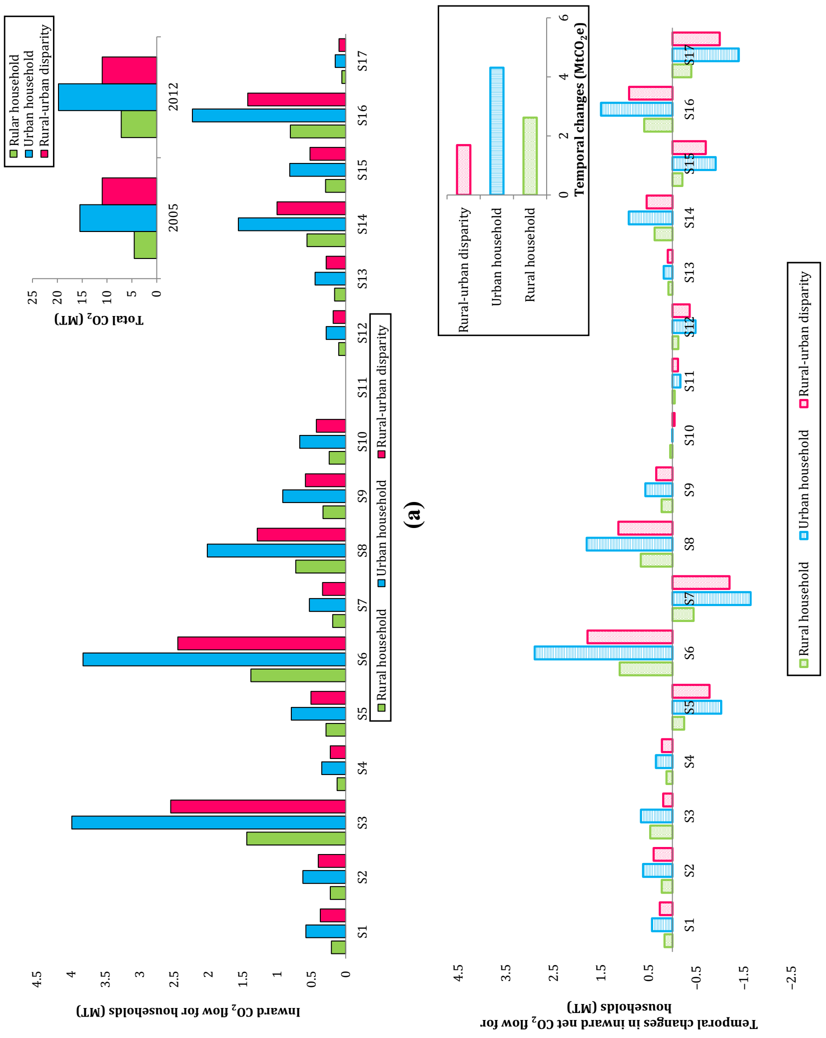
3.4 Residential impacts on sectoral CO_2 and key sectors

Given the increasing residential CO_2 emissions, it is also worth exploring how residents affected sectoral CO_2 with respect to the role of urbanization and rural–urban disparity.

3.4.1 Key sectors influenced by residential effects. Figure 7 shows there was an upward trend in residential impacts on sectoral CO_2 in Beijing where urban impacts continued being much bigger than rural impacts in 2012. Accompanying rapid urbanization, according to Wang and Yang (2016), per capita GDP was mainly responsible for residential CO_2 emissions growth in Beijing. Besides, given the unimproved rural–urban disparity, urban households have advantages over rural counterparts in many aspects such as public spending, education, information and human capital (Li *et al.*, 2014), encouraging their wider participations in economic activities and then causing more CO_2 emissions.

At the sector level, the effects of residential labor inputs on CO_2 emissions of the traditional sectors showed volatility, revealing the significance of implementing varied CO_2 mitigation measures. Figure 7(a) shows sectoral shares of residential impacts and associated rural–urban disparity basically followed the similar pattern in 2012; among all sectors, manufacturing (S3), WR trade (S6), IT (S8), transportation (S14) and technical services (S16) were top 5 sectors in sectoral emissions affected by residential effects and S6, S8 and S16 experienced the most evident positive changes in residential effects they got. However, there were some exceptional sectors witnessing a downward trend in the residential effects they received, and these sectors were construction (S5), hotels (S7), other services (S11), education (S12), tenancy services (S15) and public services (S17). Therefore, distinct CO_2 mitigation measures should be taken, that is to say, for sectors with largest residential effects and positive changes in residential effects, strict measures should be implemented, while for the sectors with the opposite conditions, their learning curves for CO_2 reduction should be valued.

3.4.2 Discussion. CO_2 emissions of urban and rural households have been emphasized in several government documents and research works (Beijing Government, 2011; 2016a, Wang and Yang, 2016). Particularly, Wang *et al.* (2012) think that the rapid urbanization played a crucial role in CO_2 growth in Beijing because the increasing income led people to improve their consumption preferences for carbon-intensive products and services. Meanwhile, Wang and Yang (2016) believe that there were growing differences between urban and rural effects on sectoral CO_2 emissions including both direct and indirect emissions in Beijing. However, few studies explained how urban and rural households



Notes: (a) Sectoral shares of total impacts in 2012 and associated rural–urban disparity and (b) temporal changes

Figure 7.
Residential impacts on sectoral CO_2 in 2005 and 2012 in Beijing

endogenously affect the intermediate IO system to reduce CO_2 emissions at the city level instead of the national level, which is the gap we attempt to fill in Section 3.4.1.

4. Conclusions, policy implication and future study

4.1 Conclusions and policy implication

To identify key sectors in carbon footprint responsibility, we introduced a concept where CO_2 responsibilities are allocated through the supply chain containing sectoral activities and interactions, applying a semi-closed IO model to make the household income–expenditure relationship endogenous through the supply chain where sectoral CO_2 emissions were calculated and the PR principle was evaluated. Thus, we used modified HEM to decompose sectoral CO_2 in terms of comparative advantages in trade, sectoral linkage and sectoral synergy. Finally, after ranking results based on the first two steps, key sectors were identified in carbon footprint responsibility. Besides, all methods and indexes were applied in the case of Beijing for the sake of proposing several feasible perspectives for CO_2 reduction in other Chinese cities.

First, the PR principle could not comprehensively reflect real origins of CO_2 emissions in Beijing, because it ignored CO_2 flows according to various sectoral activities and interactions. Besides, how comparative advantages in trade impacted CO_2 was examined: imports in Beijing continued exerting positive but not enough effects on sectoral CO_2 reduction, while its interprovincial export generated the most CO_2 emission compared to other final demand categories. Additionally, manufacturing generated the highest CO_2 embodied in trade. Therefore, the following suggestions are proposed:

- With the prerequisite of healthy economic development, CO_2 driven by interprovincial export should be reduced and import should be encouraged for CO_2 mitigation.
- Among all sectors studied, manufacturing should be the major concern in terms of sectoral CO_2 embodied in export and import.

Second, key sectors changed with types of sectoral CO_2 linkages in Beijing. For example, manufacturing had the largest internal CO_2 linkage, RE activities possessed the largest net forward CO_2 linkage and WR trade had the largest net backward CO_2 linkage, without obvious positive mixed CO_2 linkage among sectors. So, we suggest that:

- for IL, CO_2 reduction of manufacturing and transportation ranking second deserve more attention;
- for ML, maintaining low-carbon trend as a whole be necessary;
- for NFL, CO_2 induced by the production of hotels, RE activities and tendency services be reduced on a larger scale (especially, manufacturing's import be encouraged to decarbonize its NFL); and
- for NBL, CO_2 caused by the consumption of WR trade, public services and manufacturing should be alleviated.

Third, sectoral synergy, the inter-sector decomposition of sectoral linkage, measures how sectoral interactions affect CO_2 flow between sectors. Subsequently, after finding related economic drivers, key sectors were identified. Results showed inter-sector connections between manufacturing and service sectors, and between service sectors caused the largest CO_2 emissions, and inward net CO_2 flows generated from the above-mentioned sectoral interactions were more complex than their outward net CO_2 flows in terms of interacted sectors and economic drivers. Accordingly, two suggestions are proposed:

(1) in the long run, in-house high-tech improvements of manufacturing and sustainable management of service sectors be given priorities during sectoral synergy; and
(2) understanding origins and destinations of inward and outward CO_2 flows in practice be necessary for reducing CO_2, and a CO_2 flow map be made through the supply chain, indicating where to develop technologies to reduce CO_2 via sectoral synergy.

Fourth, residential impacts on CO_2 emissions from traditional sectors experienced an upward trend and urban impacts continued being much larger than rural ones. From a sector perspective, manufacturing (S3), WR trade (S6), IT (S8), transportation (S14) and technical services (S16) had the largest residential effects and S6, S8 and S16 experienced positive changes. Nonetheless, there was a downward trend in residential effects received by some sectors, including construction (S5), hotels (S7), other services (S11), education (S12), tenancy services (S15) and public services (S17). Therefore, alleviating CO_2 emissions efficiently was available because of the similarities in sectoral shares of urban effects, rural effects and associated temporal changes. More specifically, for sectors with large residential effects and largest positive changes in residential effects, strict measures should be implemented, while for the sectors with opposite conditions, their learning curves for CO_2 reduction should be summarized.

Finally, in China, there are 30 key regions sharing two common characters with Beijing: not only do they have competitive IOT, but also they have been implementing the PR principle for CO_2 accounting. So according to the case study of Beijing, three implications are applied to these regions:

- their PR principle has the possibilities of not tracking the CO_2 flow;
- the endogenous effects of the household income–expenditure relationship on CO_2 through the supply chain should be emphasized, kept in harmony with the rapid urbanization process; and
- the framework for identifying key sectors in carbon footprint responsibility could be a remainder of who to assume CO_2 responsibilities according to sectoral activities and interactions.

4.2 Future studies

More details about the impacts of both import and households on city-level CO_2 emissions could be explored. Concerning the impacts of import, there is no in-depth analysis in this paper for the source of the import-induced CO_2, because we aimed at knowing how the sectoral CO_2 emissions in Beijing were influenced by the total amount of import. In this regard, multi-region IO model has been developed for the origin of CO_2 embodied in trade for a city (Chen *et al.*, 2016b, 2013, 2016a). Additionally, more attention should be poured into the distinction between international import and interprovincial import if more improvements for CO_2 emission inventories of Beijing city are in great need. What's more, regarding the role of households played in CO_2 emissions, the endogenous effects of the household income–expenditure relationship on CO_2 emissions could be studied more comprehensively in light of income distribution and associated rural–urban disparity, as well as household consumption patterns, because related studies are rare and confined to the country level (Perobelli *et al.*, 2015).

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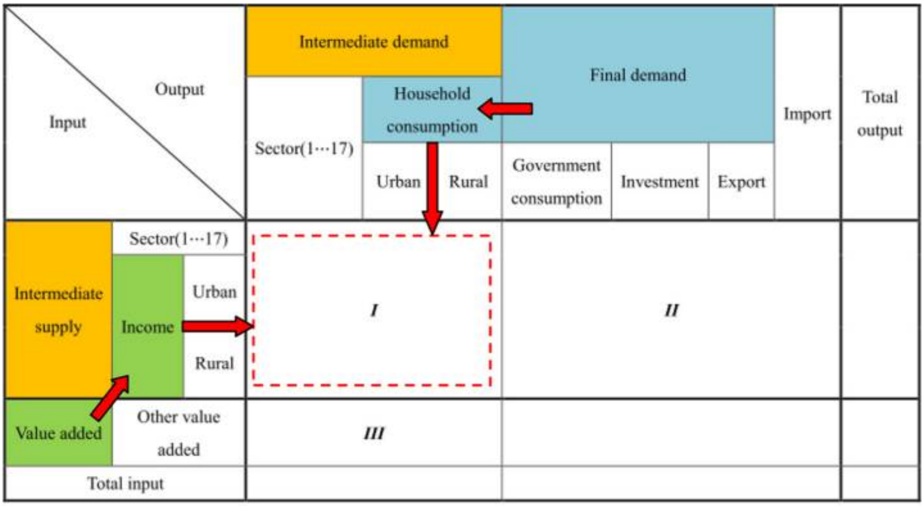
Appendix



Note: First, regard the "household consumption" (including urban and rural household consumption), originally in the "final demand" column, as the new column in "intermediate demand". Second, divide the "value added" row into "household income" (including urban and rural household income) and "other value added", and then remove the "household income" row into the "intermediate supply". Additionally, urban and rural consumption assigned to each sector is oriented from the original input–output table for Beijing. Nonetheless, limited by data availability, urban and rural income assigned to each sector is calculated based on the ratio of average urban annual income to average rural annual income. Data for urban and rural average income were from Beijing Statistical Yearbook

Figure A1.
Semi-closed input–output table

Code	Short name	42 sectors of IOT
S1	Agriculture	Farming, forestry, animal husbandry and fishery
S2	Mining	Mining and wasting of coal
		Extraction of petroleum and natural gas
		Mining of mental ores
		Mining and processing of nonmetal ores
S3	Manufacturing	Manufacture of foods and tobacco
		Manufacture of textile
		Manufacture of textile wearing apparel, footwear, caps, leather, fur, feather (down) and its products
		Processing of timbers and manufacture of furniture
		Papermaking, printing and manufacture of articles of culture, education and sports activities
		Processing of petroleum, coking, processing of nuclear fuel
		Chemical industry
		Manufacture of nonmetallic mineral products
		Smelting and rolling of metals products
		Manufacture of metal products
		Manufacture of general purpose machinery
		Manufacture of special-purpose machinery
S3	Manufacturing	Manufacture of transport equipment
		Manufacture of electrical machinery and equipment
		Manufacture of communication equipment, computer and other electronic equipment
		Manufacture of measuring instrument and machinery for cultural activity and office work
		Manufacture of artwork, other manufacture
		Scrap and waste
		Manufacture of metal products, machinery and equipment repair services
S4	Energy	Production and supply of electric power and heat power
		Production and distribution of gas
		Production and distribution of water
S5	Construction	Construction
S6	WR trade	Wholesale and retail trade
S7	Hotels	Hotel and restaurants
S8	IT	Information transmission, computer service and software
S9	Finance	Finance
S10	RE trade	Real estate trade
S11	Other services	Resident services and other services
S12	Education	Education
S13	Leisure	Culture, art, sports and recreation
S14	Transportation	Transportation, storage and post
S15	Tenancy services	Tenancy and commercial service
S16	Technical services	Compositive technical service
S17	Public services	Water, environment and municipal engineering conservancy
		Health care, social security and social welfare
		Publish manage and social organization

Table AI.
The classification of 42 sectors into 17 productive sectors

Code	Short name	57 sectors consuming energy
S1	Agriculture	Agriculture, forestry, animal husbandry and fishing
S2	Mining	Mining and washing of coal
		Extraction of petroleum and natural gas
		Mining and processing of ferrous metal ores
		Mining and processing of non-ferrous metal ores
S2	Mining	Mining and dressing of nonmetal ores
		Mining of other ores
S3	Manufacturing	Procession of food from agriculture products
		Manufacture of foods
		Manufacture of beverage
		Manufacture of tobacco
		Manufacture of textile
		Manufacture of textile wearing apparel, footwear and caps
		Manufacture of leather, furs, feather (down) and related products
		Processing of timber, manufacture of wood, bamboo, rattan, palm and straw products
		Manufacture of furniture
		Manufacture of paper and paper products
		Printing, reproduction of recording media
		Manufacture of articles for culture, education and sports activity
		Processing of petroleum, coking, processing of nuclear fuel
		Manufacture of raw chemical materials and chemical products
		Manufacture of medicines
		Manufacture of chemical fibers
		Manufacture of rubber
		Manufacture of plastics
		Manufacture of non-metallic mineral products
		Smelting and pressing of ferrous metals
		Smelting and processing of nonferrous metals
		Manufacture of metal products
		Manufacture of general purpose machinery
		Manufacture of special-purpose machinery
		Manufacture of transportation equipment
		Manufacture of electrical machinery and equipment
		Manufacture of communication equipment, computers and other electronic equipment
		Manufacture of measuring instruments and machinery for culture activity and office work
		Machinery of artwork and other manufacturing
		Recycling and disposal of waste
S4	Energy	Production and distribution of electric power and heat power
		Production and distribution of gas
		Production and distribution of water
S5	Construction	Construction
S6	WR trade	Wholesale and retail trade
S7	Hotels	Hotel and restaurants
S8	IT	Information transmission, computer services and software
S9	Finance	Finance
S10	RE trade	Real estate trade
S11	Other services	Resident services and other services
S12	Education	Education
S13	Leisure	Culture, art, sports and recreation

(*continued*)

Table AII. The classification of 57 sectors into 17 productive sectors and households

Table AII.

Code	Short name	57 sectors consuming energy
S14	Transportation	Transportation, storage, post and telecommunications
S15	Tenancy services	Tenancy and commercial services
S16	Technical service	Scientific studied, technical services and geological prospecting
S17	Public services	Public manage and social organization
		Water, environment and municipal engineering conservancy
		Health care, social security and social welfare
S18	Rural household	Rural consumption
S19	Urban household	Urban consumption

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