CO₂ emissions in Beijing: Sectoral linkages and demand drivers

Hua Liao, Célio Andrade, Julio Lumbrares, Jing Tian

1. Introduction

During industrialization, urbanization, and modernization, CO₂ emissions at the city level have become not only a main contributor to climate change (Chen et al., 2016; Wiedmann et al., 2016), but also a vital cause of poor health (Bell et al., 2007; Jacobson, 2009), leading to a crucial academic concern with multidisciplinary involvements. Consequently, to reduce CO₂ emissions at the city level, there are wide-ranging considerations, such as its calculation methods (Feng et al., 2014; Shan et al., 2016), factors (Gudipudi et al., 2016; Wang et al., 2012), forecasts (Mohareb and Kennedy, 2014; Singh and Kennedy, 2015), and control technologies and strategies (Kumar et al., 2015; Masson et al., 2014; Mi et al., 2015).

These studies indicate that a healthy city environment is a complex system full of closer inter-linkages among varied participants.

However, concerning the coupling effects among sectoral linkages, demand drivers and household participation in city-level CO₂ reduction efforts, there are two obvious problems: (1) details are lacking quantitatively in depicting how each of the above-mentioned factors influences CO₂ reduction and (2) these factors are investigated without an integrated research framework.

Regarding the relationship between sectoral linkages and CO₂, related studies have mainly focused on the country-level performance, with four methods involving the classical multiplier method (Lenzen, 2003; Zhang, 2010), sensitivity analysis (Morán and del Río González, 2007; Tarancon and Del Río, 2007), hypothetical extraction method (Schultz, 1977), and modified hypothetical extraction method (Duarte et al., 2002; Wang et al., 2013).
another, without more concerns about sectoral linkages. Related methods include decomposition methods (Hoekstra and Van den Bergh, 2003; Kopidou et al., 2016; Su and Ang, 2012), input-output model (Tian et al., 2014, 2015), and econometrics models (Talukdar and Meisner, 2001; Zhou et al., 2013).

Despite the growing significance of consumption to CO2 reduction, the relationship between detailed final demand categories and CO2 is not a main concern at the city level (Tian et al., 2013; Wang et al., 2013b). Given the emphasis on the relationship between the country-level demand drivers and CO2 emissions, relevant researches are conducted not only in each final demand category, such as trade (Dong et al., 2010), household consumption (Perobelli et al., 2015), government consumption (Zhang et al., 2017) and capital formation (Talukdar and Meisner, 2001), but also in all demand drivers like (Cansino et al., 2016; Kucukvar et al., 2014). Correspondingly, the involved methods fall into three categories: (1) econometrics models (Talukdar and Meisner, 2001; Zhang et al., 2017); (2) input-output methods (Kucukvar et al., 2014); and (3) input-output model joint with decomposition analysis (Cansino et al., 2016; Dong et al., 2010).

Referring to household participation and CO2, relevant studies can be characterized as follows: first, some micro-level studies struggle to find differences among households. Such differences include educational level, size, location, gender composition, and rebound effects, which is depicted by Zhang et al. (2015); second, some explore rural-urban disparities and related CO2 at different levels, covering multi-region level (Jacobson, 2009; Nejat et al., 2015; Zhou et al., 2015), bilateral-region level (Krey et al., 2012) and single-region level (Fan et al., 2013; Fan et al., 2016; Liu et al., 2011), by using literature review method (Krey et al., 2012; Nejat et al., 2015), the stochastic impacts by regression on population, affluence and technology (STIRPAT) model (Zhou et al., 2015), input-output analysis (Fan et al., 2016), end-use analysis (Fan et al., 2015), Divisia index decomposition (Fan et al., 2013), and Consumer Life Cycle Analysis (Liu et al., 2011). However, most studies give priorities to the ratio of the urban population to total population as the representative of household impacts; furthermore, the endogenous impact of household income and expenditure within the intermediate input-output system on CO2 is ignored during urbanization.

Beijing, characterized by a complex multilayer society involving economy, policy, and culture, has formed a stable service-oriented economic structure (Mi et al., 2015; Wang et al., 2014) and experienced increasing urban population, rising incomes, and changing lifestyle (Wang et al., 2012), with continuing urban expansion and associated growing car use (Feng et al., 2013). Meanwhile, these changes also mean reducing energy consumption and mitigating climate change continue to need great efforts (Mi et al., 2015; Wang et al., 2014). Apart from that, with closer sectoral connections and developing scale effects, it is worthwhile to explore underlying challenges in CO2 reduction in Beijing in the long run, such as (1) lag effects or the imbalance between its economic development and sectoral convergence, (2) its unique features and structure of final demand, and (3) impacts of household participation involving income and expenditure on CO2 emissions.

Based on the above analysis, the contribution of this paper includes the expansion of a semi-closed input-output (IO) model with a (modified) hypothetical extraction method (HEM) as another approach to study city-level CO2, regarding coupling effects among sectoral linkage, demand drivers, and household participation. The semi-closed IO model, pioneered in 1987 (Batey et al., 1987), emphasizes endogenous impacts of household income and consumption on the intermediate input-output system and regards households as both producers and consumers. This model is common in economic, policy, and impact analysis in the fields of energy (Behrens, 1984), agriculture (Cardenete et al., 2014), and water (Zou and Liu, 2016) instead of CO2. The modified HEM, a method used to explore sectoral linkages under input-output analysis was initially proposed in 2002 (Duarte et al., 2002) based on HEM (Paeldink et al., 1965). Just as mentioned in the relationship between sectoral linkage and CO2 emissions, there remain diverse methods, such as the classical multiplier method (Chen et al., 2017), sensitivity analysis (Liu et al., 2016), and HEM (Schultz, 1977). Different from these approaches, modified HEM could illustrate the impacts of one sector on the remaining sectors considering the combination of technological levels for each sector with components of vertical integrated consumption. It has been utilized on the domain of CO2 (Duarte et al., 2002; Perobelli et al., 2015; Wang et al., 2013a; Zhao et al., 2015).

Therefore, this paper integrates the semi-closed IO model with the modified HEM to explore the economy-wide contribution of 17 sectors and households to CO2 emissions in Beijing in 2005 and 2012. The remainder of the paper is structured as follows: section 2 explains method and data, the results analysis is depicted in section 3, and section 4 provides conclusions and policy implications.

2. Materials and methodology

2.1. Research framework

According to Fig. 1, sectoral CO2 emissions and relevant economic drivers in Beijing in 2005 and 2012 are explored by employing the semi-closed input-output (IO) model. Corresponding to the sectoral specification in economic activities, the sectoral distribution of CO2 emissions is based on a modified hypothetical extraction method (HEM), which includes internal linkage, mixed linkage, net forward linkage, and net backward linkage. Then endogenous effects of household income and consumption on CO2 emissions are discussed by using HEM.

2.2. Data source and data processing

Beijing’s input–output tables for 2005 and 2012 from Beijing Municipal Bureau of Statistics are used, and other data for 2005 and 2012 come from Beijing Statistics Yearbook. Data processing can be divided into three steps as follows: (1) Adjusting IO table according to semi-closed IO model: first, regard “household consumption” (including urban and rural household consumption), originally in the “final demand” column, as a new column in “intermediate demand”. Second, divide the “value added” row into
"household income" row (including urban and rural household income) and "other value added" row, and then remove the
"household income" row into the "intermediate supply" (see Table A1 in the Appendix). (2) Integrating the 42 sectors of IO
table and the 57 sectors consuming energy: according to Industrial Classification for Economic Activities in China, 42 sectors in
the original IO table and 57 sectors consuming energy are classified and then 17 sectors, urban household and rural household
are formed (see Tables A2 and A3 in the Appendix). (3) Changing
the original IO table and 57 sectors consuming energy: according to Industrial Classification for Economic Activities in China, 42 sectors in
the original IO table and 57 sectors consuming energy are classified and then 17 sectors, urban household and rural household
are formed (see Tables A2 and A3 in the Appendix). (3) Changing

2.3. Indexes for CO2 development based on semi-closed input-
output model

To figure out the general development of the city-level CO2
emissions, several aspects of CO2 emissions are analysed, regarding
its amount, demand drivers, efficiency and flows induced by
import. Particularly, its amount and demand drivers are calculated
directly based on the semi-closed IO model, its efficiencies are
represented by three indexes, namely, direct CO2 intensity, total
CO2 intensity and embodied CO2 intensity, and its flows caused by
import are gained according to the modified total CO2 consumption
coefficient.

The basic traditional IO model based on the non-competitive
imports assumption that imported products are identical to its total output for each sector, and $H_{\text{inc}}$, the ratio of household income to total income for each sector.

Next, change final demand, $Y^*$, without household consumption compared to $Y$:

$$Y^* = G + CA + (EX - IM)$$ (4)

Then obtain the corresponding total output, $X^*$:

$$X^* = (1 - A^*)^{-1}Y^*$$ (5)

Therefore, CO2 calculations based on the semi-closed IO model are as follows:

$$e^{\text{total}} = e(1 - A^*)^{-1}$$ (7)

$$e^{\text{embodied}} = e^{\text{total}} - e$$ (8)

where $e^{\text{total}}$ is the total CO2 intensity representing the direct and
indirect CO2 generated by per unit of total output, $e^{\text{embodied}}$ is the
embodied CO2 intensity equalling the gap between total CO2 inten-
sity and direct CO2 intensity, meaning the CO2 intensity embodied in the intermediate IO system.

Unlike the multiple-region IO analysis, the basic single-region IO
one fails to track the import-induced CO2 flow between regions.
The total CO2 consumption coefficient could be employed to
interpret the outsourced CO2 emissions via import, which helps
identify the sectors impacted most dramatically by imports in
terms of CO2 emissions. This is because it is calculated through by
the direct CO2 intensity multiplying the total consumption coeffi-
cient based on formula (1):

$$e^{\text{import}} = e\left[(1 - A^*)^{-1} - I\right]$$ (9)

where $e^{\text{import}}$ is the modified total CO2 consumption coefficient to reflect the influence of import on city-level CO2 caused by per unit of output.

2.4. CO2 linkages based on modified hypothetical extraction method

- Hypothetical Extraction Method (HEM)

As a method to study sectoral linkages, the HEM is used to
evaluate one sector’s economy-wide contributions to remaining
sectors by comparing the real economic system including this
sector with a hypothetical economic system excluding this sector.

First, the sectoral system of the city, $M$, is divided into two sectoral clusters, $M_s$ and $M_o$. $M_s$ represents the sectoral
cluster with sectors sharing the same characteristics, and $M_o$ the cluster
comprising the remaining sectors. Then, the total sectors of the city

\[
A^* = \begin{bmatrix} A & H_{\text{inc}} \\ H_{\text{inc}} & 0 \end{bmatrix}
\]

where $A^*$ is the technological coefficient matrix of the semi-closed
IO model, and $A^*$ includes $A$, the technological coefficient matrix of the
basic IO model, $H_{\text{inc}}$, the ratio of household consumption to
total output for each sector, and $H_{\text{inc}}$, the ratio of household income
to total income for each sector.
can be grouped as follows:

\[
I = \begin{bmatrix}
M_{b,s} & M_{b,-s} \\
M_{s,s} & M_{s,-s}
\end{bmatrix}
\]

(10)

Next, set two scenarios: scenario 1 represents the real economic system and scenario 2 represents the hypothetical economic system where a certain sector is extracted.

Under scenario 1, CO2 levels are calculated as follows:

\[
\begin{bmatrix}
C_s \\
C_{-s}
\end{bmatrix} = \begin{bmatrix}
e_s & 0 \\
0 & e_{-s}
\end{bmatrix} \begin{bmatrix}
B_{s,s} & B_{s,-s} \\
B_{s,-s} & B_{s,s}
\end{bmatrix} \begin{bmatrix}
Y_s^* \\
Y_{-s}^*
\end{bmatrix}
\]

(11)

where \((I-A)^{-1} = \begin{bmatrix}
B_{s,s} & B_{s,-s} \\
B_{s,-s} & B_{s,s}
\end{bmatrix}\)

Under scenario 2, when sector \(s\) is extracted, CO2 levels are calculated using

\[
\begin{bmatrix}
C_s \\
C_{-s}
\end{bmatrix} = \begin{bmatrix}
e_s & 0 \\
0 & e_{-s}
\end{bmatrix} \begin{bmatrix}
(B_{s,s} - (I - A_{s,s}^*)^{-1} & 0 \\
0 & (I - A_{s,-s}^*)^{-1}
\end{bmatrix} \begin{bmatrix}
Y_s^* \\
Y_{-s}^*
\end{bmatrix}
\]

(12)

The difference between scenario 1 and scenario 2 is explained in equations (13) and (14).

\[
C_{bef} - C_{aft} = \begin{bmatrix}
e_s & 0 \\
0 & e_{-s}
\end{bmatrix} \begin{bmatrix}
C_{bef} \\
C_{aft}
\end{bmatrix}
\]

(13)

\[
C_{bef} - C_{aft} = \begin{bmatrix}
B_{s,s} - (I - A_{s,s}^*)^{-1}B_{s,-s} \\
B_{s,-s} - (I - A_{s,-s}^*)^{-1}
\end{bmatrix} \times \begin{bmatrix}
Y_s^* \\
Y_{-s}^*
\end{bmatrix}
\]

(14)

where \(C_{bef}\) is calculated under scenario 1 and \(C_{aft}\) under scenario 2.

**Modified HEM**

Based on the modified HEM (Duarte et al., 2002), CO2 linkages among sectors could be decomposed into four elements, that is, internal linkage (IL), mixed linkage (ML), net forward linkage (NFL), and net backward linkage (NBL):

\[
IL = u_s^e(1 - A_{s,s}^*)^{-1}Y_s^*
\]

where \(IL\) refers to the CO2 generated by the products and services created by \(M_s\) itself to satisfy the final demand of \(M_s\)

\[
ML = u_s^eB_{s,s}(1 - A_{s,s}^*)^{-1}Y_s^*
\]

where \(ML\) is the CO2 generated by the products and services created by \(M_s\) firstly but then used by another sector (cluster), \(M_{-s}\), and repurchased and reprocessed by \(M_s\) at meeting the final demand of \(M_s\)

\[
NFL = u_s^eB_{s,-s}Y_{-s}^*
\]

(15)

\[
NBL = u_s^eB_{s,s}Y_{s}^*
\]

where, to satisfy the final demand of \(M_s\), \(Y_s^*\), CO2 (NBL) would be generated during the direct and indirect production of another sector (cluster), \(M_{s,-s}\).

2.5. Impacts of household income and expenditure on CO2 emissions

Based on the semi-closed IO model and HEM described above, impacts of household income and expenditure on CO2 levels within the economic system could be gained by extracting the “income row” and “consumption column” of the economic system, respectively from the whole economic system. Furthermore, the impacts could be studied at three levels: urban (rural) households, 17 sectors, and rural (urban) counterparts.

3. Result analysis and discussion

3.1. Historical variation and characteristics of CO2 emissions in Beijing

3.1.1. CO2 emissions caused by energy consumption

Affected by energy consumption directly, total CO2 emissions in Beijing increased from 135.66 Mt in 2005 to 171.85 Mt in 2012, with main concentrations arising from manufacturing (S3), transportation, storage and post (S14), and urban households (S19) (see Fig. 2). This indicates that a shift in economic structure from industrialized to service-driven activities could not achieve the expected low carbonization. Furthermore, households have an increasingly important impact on CO2 levels, partly due to urbanization causing population migration, changing lifestyles, increasing motor vehicle utilization, and so on.

3.1.2. CO2 emissions driven by final demand

In line with the semi-closed IO model, household income-expenditure relationship is among the intermediate IO system and then imposes the endogenous effects on this system. Therefore, there is one difference between other precious studies where household in Beijing is interpreted as the consumer (Feng et al., 2014; Guo et al., 2012; Wang et al., 2013b) and the section where household are considered as both the producer and consumer.

Accompanying closer trade links between Beijing and its surrounding regions, the increasing total CO2 emissions were driven mostly by Beijing’s interprovincial export (Fig. 3a). By contrast, CO2 emissions induced by other final demand categories grew at a shrinking small scale (Fig. 3a). Therefore, Beijing should adjust the structure of final demand to reduce CO2 emissions with the prerequisite of maintaining healthy operation of sectoral economies.

To determine the sectoral shares of CO2 driven by each final demand category, results in 2012 are as follows (Fig. 3b and c): (1) manufacturing (S3), transportation, storage, and post (S14), and urban households (S19) generated most CO2 by Beijing’s interprovincial export; and (2) manufacturing (S3) caused the largest amount of CO2 leakage because its government consumption and capital formation were import–dependent. These findings indicate the significance of import and export to CO2 reductions in the manufacturing (S3) sector, along with reductions in Beijing’s interprovincial export of the transportation, storage, and post (S14) and urban household (S19) in Beijing.

3.1.3. CO2 emissions embodied in the intermediate input-output system

Whether “intensity targets” could be effective for CO2 reduction,
3.1.4. CO2 emissions outsourced via import

In terms of embodied CO2 intensity, which refers to embodied CO2 per unit of output in the intermediate input-output system, Fig. 4c indicates that (1) urban households (S19) and real estate activities (S10) ranked as the top two sectors; (2) manufacturing (S2), mining (S3), and hotels and restaurants (S7) ranked in the bottom three sectors due to their imports; and (3) most sectors, especially among secondary industries, reduced CO2 arising from the intermediate input-output system, according to their negative value of embodied CO2 intensity (see Fig. 4c).

3.2. CO2 linkages among sectors in Beijing

In terms of impacts of industry structure on CO2 emissions in Beijing, most studies have advocated its significance. For instance, Beijing is supposed to act as a reminder to other Chinese cities with regard to the development of its industrial structure (Tian et al., 2013). In addition, it is worth examining the potential impacts of industrial structure on energy-related CO2 in Beijing (Mi et al., 2015), to mitigate climate change. For CO2 decomposition along supply and demand chains in this section, based on the modified hypothetical extraction method, CO2 flows were decomposed corresponding to sectoral specifications, consisting of internal linkage (IL), mixed linkage (ML), net forward linkage (NFL) and net backward linkage (NBL).

3.2.1. Overview of CO2 linkages among sectoral clusters

As shown in Fig. 5, in Beijing, sectoral convergence has not progressed smoothly, leading to further CO2 emissions accumulating in the closed circuits of sectoral supply and demand (i.e., IL). By contrast, with industrial structure upgrading and import development, CO2 emission reductions were induced along the NFL of secondary sectors and NBL of both secondary and tertiary industry. In addition, tertiary industry continued to generate CO2 in each segment of the supply and demand chains, owing to its wide-ranging contributions to Beijing’s GDP. In particularly, for a certain industry, its CO2 levels in 2012 compared to those in 2005: (1) more CO2 emissions were induced by its increasing IL; (2) few CO2 emissions were caused by ML; (3) for secondary industry, its imports started encouraging the largest CO2 leakages considering...
(a) Total CO$_2$ emissions driven by final demand

(b) Sectoral CO$_2$ in 2005

(c) Sectoral CO$_2$ in 2012

Fig. 3. Sectoral CO$_2$ emissions driven by final demand in Beijing in 2005 and 2012 (unit: MtCO$_2$e).

(a) Direct CO$_2$ intensity
(b) Total CO$_2$ intensity
(c) Embodied CO$_2$ intensity

Fig. 4. Direct CO$_2$ intensity, total CO$_2$ intensity and embodied CO$_2$ intensity in Beijing in 2005 and 2012 (unit: tCO$_2$e per ten thousand yuan in constant 2005 price).
negative NFL and NBL; and (4) for tertiary industry, CO2 emissions caused by NBL remained the highest and those from NFL continued to be positive.

3.2.2. Sectoral shares of CO2 linkages

CO2 emissions caused by self-sufficient production in Beijing increased substantially. Among sectors, manufacturing (S3), and transportation, storage and post (S14) contributed the most. Specifically, the sectoral IL of CO2 levelled out at the range of 0–10 Mt CO2 with an increasing trend (see Fig. 6a). Besides, the IL of the top two sectors including manufacturing (S3), and transportation, storage, and post (S14) had different causes: S3 was driven by its larger final demand while S14 by its higher direct CO2 intensity. In this regard, figuring out the detailed drivers of sectoral IL is also important for CO2 reduction and needs more in-depth analysis of sectoral characteristics.

Overall, the ML of CO2 contributed the least to the increased CO2 emissions in Beijing, compared to other types of sectoral linkages. Furthermore, when it comes to sectoral shares of ML, manufacturing (S3) played the paramount role in ML: the ML of manufacturing (S3) was greatest in 2005 but by 2012, it had fallen to the least (see Fig. 6b).

Following NFL of CO2 within the sectoral network, obvious changes existed in the NFL of secondary industry, rather than that of other industries. This is largely because in secondary industry, manufacturing (S3) presented the most evident changes in NFL (see Fig. 6c).

Tertiary industry experienced an upward trend in the positive net NBL of CO2. Typically, along NBL, some sectors clearly increased their CO2 emissions and they were wholesale and retail trade (S6), information transformation, computer services and software (S8), and finance (S9). At the same time, CO2 reductions were encouraged by import-dependent consumption, with a declining intersector difference. Particularly, manufacturing (S3) and construction (S5) had obvious CO2 leakages due to their producers’ import and the large amount of Beijing’s interprovincial export for their consumption (Fig. 6d).

3.3. Impacts of household income and expenditure on CO2 emissions

In the field of impacts of household consumption on CO2 emissions, situations where households serve as consumers have been considered in depth at the country level (Wiedenhofer et al., 2017) or at the city level (He et al., 2016; Wang and Yang, 2016). Different from this thinking, endogenous effects of household on intermediate input–output system are considered through household income-expenditure relation. Household income-oriented impacts on their own CO2 emissions intended to be more than household expenditure-oriented impacts in Beijing (see Fig. 7a), but they all exceeded household impacts on sectoral CO2 as well as CO2 emission of households excluding itself (see Fig. 7a–d). Residential sectors preferred saving money to consuming at present in order to avoid future risks, although household income increased thanks to the country’s overall economic development. Meantime, for each household, the imbalanced results among its own CO2, sectoral CO2, and CO2 of households excluding themselves showed that individual households were not the main participant of economic activities of sectors and other households.

Rural–urban disparities in both supply-side and demand-side CO2 were widening while those in sectoral CO2 were narrowing (Fig. 7c–f). However, the reasons behind such changes were similar but different in the impact direction. Accompanying the limits on the household registration system and rural-urban disparities in income in the context of rapid urbanization, differing household

<table>
<thead>
<tr>
<th>Year</th>
<th>Producer</th>
<th>2005</th>
<th>2012</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>S7</td>
<td>-0.0068</td>
<td>0.8934*</td>
</tr>
<tr>
<td>S1</td>
<td>-0.0048</td>
<td>-0.2154</td>
<td>-0.0007</td>
</tr>
<tr>
<td>S3</td>
<td>-0.0071</td>
<td>0.5745*</td>
<td>-0.0168</td>
</tr>
<tr>
<td>S4</td>
<td>-0.0047</td>
<td>-0.0614</td>
<td>-0.0030</td>
</tr>
<tr>
<td>S5</td>
<td>-0.0073</td>
<td>0.4608</td>
<td>-0.0058</td>
</tr>
<tr>
<td>S6</td>
<td>-0.0086</td>
<td>-0.1134</td>
<td>0.9723*</td>
</tr>
<tr>
<td>S7</td>
<td>0.9957</td>
<td>-0.0477</td>
<td>-0.2789</td>
</tr>
<tr>
<td>S8</td>
<td>-0.0051</td>
<td>-0.2648</td>
<td>-0.0092</td>
</tr>
<tr>
<td>S9</td>
<td>-0.0029</td>
<td>-0.1162</td>
<td>-0.0051</td>
</tr>
<tr>
<td>S10</td>
<td>-0.0030</td>
<td>-0.1228</td>
<td>-0.0048</td>
</tr>
<tr>
<td>S11</td>
<td>0.0060</td>
<td>-0.0242</td>
<td>-0.0116</td>
</tr>
<tr>
<td>S12</td>
<td>-0.0063</td>
<td>-0.0966</td>
<td>-0.2291</td>
</tr>
<tr>
<td>S13</td>
<td>0.0062</td>
<td>-0.0566</td>
<td>-0.2672</td>
</tr>
<tr>
<td>S14</td>
<td>-0.0064</td>
<td>-0.2436</td>
<td>-0.0055</td>
</tr>
<tr>
<td>S15</td>
<td>-0.0058</td>
<td>-0.2255</td>
<td>-0.0098</td>
</tr>
<tr>
<td>S16</td>
<td>-0.0056</td>
<td>-0.2808</td>
<td>-0.0145</td>
</tr>
<tr>
<td>S17</td>
<td>0.0072</td>
<td>-0.0123</td>
<td>-0.3087</td>
</tr>
<tr>
<td>S18</td>
<td>-0.0024</td>
<td>-0.0503</td>
<td>-0.0022</td>
</tr>
<tr>
<td>S19</td>
<td>-0.0124</td>
<td>-0.0249</td>
<td>-0.3093</td>
</tr>
<tr>
<td>Sum</td>
<td>0.8871</td>
<td>0.7256</td>
<td>-3.2872</td>
</tr>
</tbody>
</table>

Note: * are sectors that cannot benefit from their import as much as other sectors do when serving as producers.
participation levels in economic activities have been stimulated in Beijing. Consequently, through incomes and expenditures, urban households could influence supply-side and demand-side CO2, as well as sectoral CO2 emissions more than rural households. Additionally, sectoral CO2 emissions were not only influenced by households but also by import and final demand within the economic system (as mentioned before, the whole system was greatly influenced by import), so they were not mainly responsible for the impacts of household on total emissions. Nonetheless, despite the fact above, the direct CO2 intensity of urban households decreased but that of rural households increased in 2012 (see Fig. 7c and d). Therefore, both amount and intensity of CO2 emissions caused by households should be considered when designing environmental policies or rules.

However, urban and rural households had some features in common (see Fig. 7c and d): (1) impacted by households, CO2 leakages existed in some sectors like agriculture (S1), manufacturing (S3), wholesale and retail trade (S6), and transport, storage, and post (S14); (2) affected by households, tertiary sectors like hotels and restaurants (S7), real estate activities (S10), and education (S15) generated more CO2. These similarities suggest the necessity of considering linkages between households and typical sectors for designing environmental policies or adopting related countermeasures.

4. Conclusions and policy implications

Comprehensive understanding of CO2 emissions in Beijing could boost the effectiveness of CO2 mitigation measures. This paper evaluated total CO2 in Beijing in 2005 and 2012 in terms of three aspects: Aspect 1 considers the amount, drivers, efficiency, and flow of CO2; Aspect 2 focuses on allocation of CO2 according to sectoral linkages; and Aspect 3 points to household impacts on CO2. Then, corresponding policy implications were considered. All results were gained by integrating a semi-closed input-output model with a hypothetical extraction thinking.

4.1. Conclusions

- **Aspect 1**

  First, a shift in economic structure from industrialized to service-driven activities in Beijing did not aid a lot in low carbonization. It is because the total CO2 emissions experienced an increase trend mainly coming from manufacturing; transportation, storage, and post; and urban households. Secondly, accompanying closer trade connection between Beijing and its surrounding regions or areas, the increases in total CO2 were driven mostly by Beijing’s interprovincial export while less driven by other final demand categories. Thirdly, there were obvious differences between the direct and total CO2 intensity considering the total and sectoral distribution, indicating that evident changes came to CO2 embodied in the intermediate IO system correspondingly. Both economy and CO2 reduction could benefit from import in Beijing, regarding the sectoral distribution of total CO2 consumption coefficients of agriculture; manufacturing; wholesale and retail trade; and transport, storage, and post in 2012.

- **Aspect 2**

  Sectoral convergence in Beijing has not progressed smoothly, causing more CO2 emissions accumulated in closed circuits of sectoral supply and demand. Among the sectors, manufacturing; and transportation, storage, and post contributed the most. But more CO2 reductions came from the NFL and NBL of secondary sectors particularly for manufacturing. This phenomenon was partly driven by both industrial structure upgrading and import developments in Beijing. Few CO2 emissions were caused by ML across all sectors, among which manufacturing played the leading role. In addition, tertiary industry continued to generate CO2 in each part of the supply and demand chains with the related smaller inter-sector differences, owing to its wide-ranging contribution to Beijing’s GDP.
Households’ income-oriented impacts on their own CO₂ were greater than household expenditure-oriented impacts in Beijing, but they all exceeded household impacts on sectoral CO₂ and CO₂ emission of households excluding themselves. Besides, rural–urban disparities in both supply-side and demand-side CO₂ were widening while that in sectoral CO₂ was narrowing. Despite these divergences, urban and rural impacts on sectoral CO₂ have something in common: (1) some tertiary sectors (e.g., hotels and restaurants; real estate activities; and education) generated the increased CO₂ emissions with household effects; (2) some sectors (e.g., agriculture, manufacturing; wholesale and retail trade; and transport, storage, and post) had the obvious carbon leakage due to the household participation. Additionally, the direct CO₂ intensity of urban households decreased whereas that of rural households increased in 2012.

4.2. Policy implications

In terms of aspect 1, Beijing could focus on mitigating CO₂ emissions from urban households.
emissions from manufacturing; transportation, storage, and post; and urban household sectors. For economic drivers, adjusting the structure of final demand to reduce CO2 emissions is also crucial with the prerequisite of the healthy operation of sectoral economies. More importantly, it is worthwhile to combine the consideration of sectoral characteristics with sectoral final demand categories in the field of CO2 alleviation. For instance, these findings support the significance of CO2 reduction in both import and export of Manufacturing, along with the interprovincial export of transportation, storage and post and urban household. Given that sectoral CO2 intensities varied sustainably in the intermediate input-output system, final demand side, and the entire economic system, if environmental policies only consider direct CO2 intensity, measures will not be implemented efficiently and effectively. Besides, although the continuing encouragement of imports improved both the economy and environment in Beijing, attention could be paid to how to select feasible sectors that could achieve environmental and economic benefits.

Regarding aspect 2, it is necessary to decompose sectoral CO2 emissions according to sectoral specifications along supply and demand chains. Inefficiency of environmental policies and regulations could also arise if they are only implemented in some certain sectors which would generate further direct CO2 emissions, particularly when differing sectoral contributions to CO2 emissions are considered in Beijing. For example, CO2 emissions from manufacturing were caused mainly by its internal linkage among sectors (as were those from the transport, storage, and post sector), but its net forward and net backward linkages could aid in mitigating CO2 emissions. Therefore, different activities of the manufacturing sector along its supply and demand chain allow for CO2 emissions to be decomposed.

With respect to aspect 3 indicating household CO2 emissions have greatly contributed to the increased CO2 in Beijing, results suggest that CO2 reductions be increased more evidently by decreases in household income-oriented impacts than expenditure-oriented impacts. In addition, both the amount and intensity of CO2 emissions caused by households could be considered together, along with the emphasis on thinking of the CO2 linkages between households and typical sectors for designing environmental policies or rules. Furthermore, aiming at exploring future potentials for CO2 reduction, urban-rural integration in Beijing deserves further promotions.

Finally, based on sectoral economy-wide effects in the field of CO2, related incentive-based measures such as the emissions trading scheme (ETS) and the carbon tax for CO2 reduction could be reconsidered. As we know, the fundamental step of the two main mechanisms concerns the calculation of carbon emissions. In practice, according to the current accounting principle in Beijing’s ETS, the direct CO2 emissions are calculated through multiplying the amount of fossil fuel consumption of selected energy-intensive sectors by direct CO2 emission factor which will be replaced by the indirect CO2 emission factor of electricity consumption when the indirect CO2 emissions are measured. Nonetheless, out of the empirical results gained from the semi-closed IO model integrated with HEM in this paper, CO2 emissions from energy consumption are the integrated outcomes in terms of direct CO2 emission factor, the Leontief inverse (i.e., total requirements matrix) and final demand categories. Therefore, the reassessments of CO2 emission could be required, ensuring the equality of its implementation for ETS.

4.3. Future studies

Based on the analysis presented in this paper, information collected on CO2 emissions was considered to determine policy implications on sectoral CO2 in terms of how each sector influences (1) the overall economic system, and (2) the intermediate input-output system. However, in the field of CO2, identifying the key sector would pinpoint which sector has the largest potential to trigger CO2 throughout the economy, thus helping understand the exact origins of CO2 flows and aiding in evaluating industrial policy efficiency and ensuring adoption of feasible policies. Therefore, based on identifying the key sector, improved understanding of embodied CO2 flow and carbon balance among sectors is a recommended avenue for future researches.

Acknowledgements

We thank the financial supports from the China’s National Key R&D Program (2016YFA0602801, 2016YFA0602603), National Natural Science Foundation of China (No. 71322306, 71273027, 71521002, 71673026). The views expressed in this paper are solely authors’ own and do not necessarily reflect the views of the supporting agencies and authors’ affiliations.

Appendix
### Table A2
The classification of 42 sectors into 17 sectors.

<table>
<thead>
<tr>
<th>Code</th>
<th>17 sectors</th>
<th>42 sectors of IOT</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>Agriculture</td>
<td>Farming, Forestry, Animal Husbandry and Fishery</td>
</tr>
<tr>
<td>S2</td>
<td>Mining</td>
<td>Mining and Wasting of Coal, Extraction of Petroleum and Natural Gas, Mining of Mental Ores, Mining and Processing of Nonmetal Ores</td>
</tr>
<tr>
<td>S4</td>
<td>Production and Supply of Electric Power and Heat Power</td>
<td>Production and Supply of Electric Power and Heat Power, Production and Distribution of Gas, Production and Distribution of Water</td>
</tr>
<tr>
<td>S5</td>
<td>Construction</td>
<td>Construction</td>
</tr>
<tr>
<td>S6</td>
<td>Wholesale and retail Trade</td>
<td>Wholesale and retail Trade</td>
</tr>
<tr>
<td>S7</td>
<td>Hotel and Restaurants</td>
<td>Hotel and Restaurants</td>
</tr>
<tr>
<td>S8</td>
<td>Information Transmission, Computer Service and Software</td>
<td>Information Transmission, Computer Service and Software</td>
</tr>
<tr>
<td>S9</td>
<td>Finance</td>
<td>Finance</td>
</tr>
<tr>
<td>S10</td>
<td>Real Estate Trade</td>
<td>Real Estate Trade</td>
</tr>
<tr>
<td>S11</td>
<td>Resident Services and Other Services</td>
<td>Resident Services and Other Services</td>
</tr>
<tr>
<td>S12</td>
<td>Education</td>
<td>Education</td>
</tr>
<tr>
<td>S13</td>
<td>Culture, Art, Sports and Recreation</td>
<td>Culture, Art, Sports and Recreation</td>
</tr>
<tr>
<td>S14</td>
<td>Transportation, Storage and Post</td>
<td>Transportation, Storage and Post</td>
</tr>
<tr>
<td>S15</td>
<td>Tenancy and Commercial Service</td>
<td>Tenancy and Commercial Service</td>
</tr>
<tr>
<td>S16</td>
<td>Composite Technical Service</td>
<td>Composite Technical Service</td>
</tr>
<tr>
<td>S17</td>
<td>Public and social management</td>
<td>Water, Environment and Municipal Engineering Conservancy, Health Care, Social Security and Social Welfare, Publish Manage and Social Organization</td>
</tr>
</tbody>
</table>

### Table A3
The classification of 57 sectors into 17 sectors and households.

<table>
<thead>
<tr>
<th>Code</th>
<th>17 sectors and households</th>
<th>57 sectors consuming energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>Agriculture</td>
<td>Agriculture, forestry, animal husbandry and fishing</td>
</tr>
<tr>
<td>S2</td>
<td>Mining</td>
<td>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, Mining and dressing of nonmetal ores, Mining of other ores</td>
</tr>
<tr>
<td>S3</td>
<td>Manufacturing</td>
<td>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</td>
</tr>
</tbody>
</table>

(continued on next page)
<table>
<thead>
<tr>
<th>Code</th>
<th>17 sectors and households</th>
<th>57 sectors consuming energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>S3</td>
<td>Manufacturing</td>
<td>Manufacture of measuring instruments and machinery for culture activity and office work</td>
</tr>
<tr>
<td>S4</td>
<td>Production and distribution of electricity, gas and water</td>
<td>Production and distribution of electric power and heat power</td>
</tr>
<tr>
<td>S5</td>
<td>Construction</td>
<td>Construction</td>
</tr>
<tr>
<td>S6</td>
<td>Wholesale and retail trade</td>
<td>Wholesale and retail trade</td>
</tr>
<tr>
<td>S7</td>
<td>Hotel and restaurants</td>
<td>Hotel and restaurants</td>
</tr>
<tr>
<td>S8</td>
<td>Information transmission, computer services and software</td>
<td>Information transmission, computer services and software</td>
</tr>
<tr>
<td>S9</td>
<td>Finance</td>
<td>Finance</td>
</tr>
<tr>
<td>S10</td>
<td>Real estate trade</td>
<td>Real estate trade</td>
</tr>
<tr>
<td>S11</td>
<td>Residents service and services</td>
<td>Residents service and services</td>
</tr>
<tr>
<td>S12</td>
<td>Education</td>
<td>Education</td>
</tr>
<tr>
<td>S13</td>
<td>Culture, art, sports and recreation</td>
<td>Culture, art, sports and recreation</td>
</tr>
<tr>
<td>S14</td>
<td>Transportation, storage, and post</td>
<td>Transportation, storage, post and telecommunications</td>
</tr>
<tr>
<td>S15</td>
<td>Tenancy and commercial services</td>
<td>Tenancy and commercial services</td>
</tr>
<tr>
<td>S16</td>
<td>Composutive Technical Service</td>
<td>Scientific studied, technical services and geological prospecting</td>
</tr>
<tr>
<td>S17</td>
<td>Public and social management</td>
<td>Public manage and social organization</td>
</tr>
<tr>
<td>S18</td>
<td>Rural Household</td>
<td>Water, environment and municipal engineering conservancy</td>
</tr>
<tr>
<td>S19</td>
<td>Urban Household</td>
<td>Health care, social security and social welfare</td>
</tr>
</tbody>
</table>

References


