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Key Points:
- New indices are proposed to quantify the dynamic carbon emission linkages for a city
- Manufacturing-related carbon emission linkages have been increasingly transferred outside the city of Beijing since 2005
- Carbon emission linkages from the energy sector to services sectors remain important in Beijing's local economy during urbanization

Supporting Information:
- Supporting Information S1

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Dynamic Carbon Emission Linkages Across Boundaries

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Abstract Cities are increasingly linked to domestic and foreign markets during rapid globalization of trade. While transboundary carbon footprints of cities have been recently highlighted, we still have limited understanding of how carbon emission linkages between sectors are reshaping urban carbon footprints through time. In this study, we propose an integrated input-output approach to trace the dynamics of various types of carbon emission linkages associated with a city. This approach quantifies full linkages in the urban carbon system from both production- and consumption-based perspectives. We assess the dynamic roles that economic sectors and activities play in manipulating multiscale linkages induced by local, domestic, and international inputs. Using Beijing as a case study, we find that imports from domestic and foreign markets have an increasing impact on the city's carbon footprint with more distant linkages during the period from 1990 to 2012. The manufacturing-related carbon emission linkages have been increasingly transferred outside the urban boundary since 2005, while the linkages from the energy sector to services sectors remain important in Beijing's local economy. Applying systems thinking to input-output linkage analysis provides important details on when and how carbon emission linkages evolved in cities, whereby sector-oriented and activity-oriented carbon mitigation policies can be formulated.

Plain Language Summary Cities are increasingly linked to domestic and foreign markets during rapid globalization of trade. In this study, we propose an integrated approach to answer the question: what drives the carbon emissions from urban activities? We assess the dynamic roles that economic sectors and activities play in manipulating carbon flows related to local, domestic, and international inputs. Using Beijing as a case study, we find that imports from domestic and foreign markets have an increasing impact on the city's carbon flows from 1990 to 2012. The manufacture-related carbon emission has been increasingly transferred outside the urban boundary since 2005, and the connection of energy sector with services sectors remains important in Beijing's local economy. This study provides important details on when and how carbon emission alters in cities, whereby informed carbon mitigation policies can be formulated.

1. Introduction

The Paris Climate Agreement, signed by 197 countries, set forth an ambitious goal of constraining the global average temperature increase below 1.5–2.0 °C in this century compared to preindustrial levels (United Nations Framework Convention on Climate Change, 2017). Coordinated and efficient actions on decarbonization will most likely occur at subnational levels such as cities. Already, more than 200 global cities have set clear goals of reducing carbon emissions (C40 & Arup, 2014). Recent evidence shows that 71–76% of CO_2 emissions from global final energy use can be ascribed to cities (Seto et al., 2014). Urban decarbonization has been an indispensable part of the climate change mitigation picture yet a challenging task that needs comprehensive accounting and regulation tools (Creutzig et al., 2015; Ramaswami et al., 2016; Rosenzweig et al., 2010; Seto et al., 2011, 2012).

In-boundary accounting approaches (Harvey, 1993; Shan et al., 2017; Shearer et al., 2017) have been widely applied to measure urban carbon emission. Recent studies suggest that transboundary carbon flows are also crucial for quantifying urban carbon footprints due to the national or worldwide trade among cities (Chavez & Ramaswami, 2011; Jones & Kammen, 2011, 2014; Lenzen & Peters, 2010; Singh & Bakshi, 2014). Frameworks of urban carbon footprint incorporating in-boundary emissions and various components of transboundary emissions have been successively established, such as territorial plus electricity-related carbon footprint (Dhakal, 2009; Kennedy et al., 2009; Liu et al., 2012; Sovacool & Brown, 2010), community-wide infrastructure carbon footprint (Chavez & Ramaswami, 2013; Ramaswami et al., 2011, 2008), consumption-based carbon footprint (Feng et al., 2014; Mi et al., 2016), final-demand (or embodied) carbon footprint (Chen & Chen, 2017), and controlled carbon footprint (Chen & Chen, 2016a; Chen & Zhu, 2019). The difference in system boundaries of these variants of carbon footprints have been covered in Lin et al. (2015). It was reported that carbon emission from imports can contribute over one half of the total carbon footprint driven by urban consumption (Chen et al., 2016), and carbon intensities of production often differ across regions (Wiedmann, 2009).

An input-output-based, three-scale model was established to decompose a city's footprint into flows induced by local production, domestic input, and international import (Chen et al., 2013; Li et al., 2016; Shao et al., 2016). Other studies applied a similar logic by connecting an urban input-output model with a global multi-region input-output model (MRIO) but with higher resolution regarding domestic and foreign regions (Hu et al., 2016; Lin et al., 2015; Wiedmann, 2017; Wiedmann et al., 2016). It is essential to go beyond carbon footprint accounting and target the most influential sectors and linkages for effective mitigation actions (Hubacek et al., 2016; Minx et al., 2013). Early carbon input-output modeling combined with network analysis provides a basis for tracking sector and activity levels (Chen & Chen, 2012; Chen et al., 2015; Lin et al., 2015, 2017). During urbanization the carbon emission linkages (i.e., carbon emission flows into, out of, or cycled back to economic sectors) can change dramatically. Scholars have applied system-based indicators to quantify the importance of various carbon linkages related to economic sectors (Chen & Chen, 2017; Zhao et al., 2015). However, the current set of indicators does not consider the dynamic role that economic sectors and activities play in the changing economy. An optimal way to do so would be to compare the relative dynamics of sectors and activities with simultaneous changes occurring at the level of the whole economy. This will be a primary step for urban decarbonization to pinpoint dominant linkages behind the nested configuration of carbon flows within or across urban boundaries.

In this paper, we develop an integrated approach termed input-output network linkage analysis (IONLA) to trace the dynamics of carbon linkages associated with the economic sectors within or across Beijing's urban boundaries. By fusing input-output analysis, linkage analysis, and network modeling, we are able to tackle how and why carbon emission linkages evolve in a fast-growing city. The proposed indicators for assessing dynamic linkage can reveal the effect of inherent activities of a sector or its interaction (trade) with the rest of the urban economy.

2. Materials and Methods

2.1. Technical Framework for IONLA

A stepwise process is designated for the development of IONLA and its application to revealing carbon linkages (Figure 1). First, using material flow analysis and input-output analysis, we conduct a time series inventory of direct carbon emissions from energy use and industrial processes and trace the indirect emissions from upstream supply chains that are related to the urban economy. This poses a question of how much carbon has been emitted from economic sectors from both production- and consumption-based perspectives. Second, to find out which sectors dominate the urban carbon linkages, we combine input-output analysis and linkage analysis to quantify backward and forward linkages, revealing the role economic sectors play in transferring carbon emissions. Finally, we decompose the carbon flow system of a city into carbon linkage networks induced by local production, domestic input, and import. This network extension of linkage analysis allows us to address the dynamics of carbon flows in specific economic activities.

2.2. Carbon Flows Accounting Cross Boundaries

Input-output analysis has been a streamlined tool for embodied carbon accounting at multiple scales (Liu et al., 2015; Minx et al., 2009; Peters, 2010), and it has been increasingly applied to city-level footprints

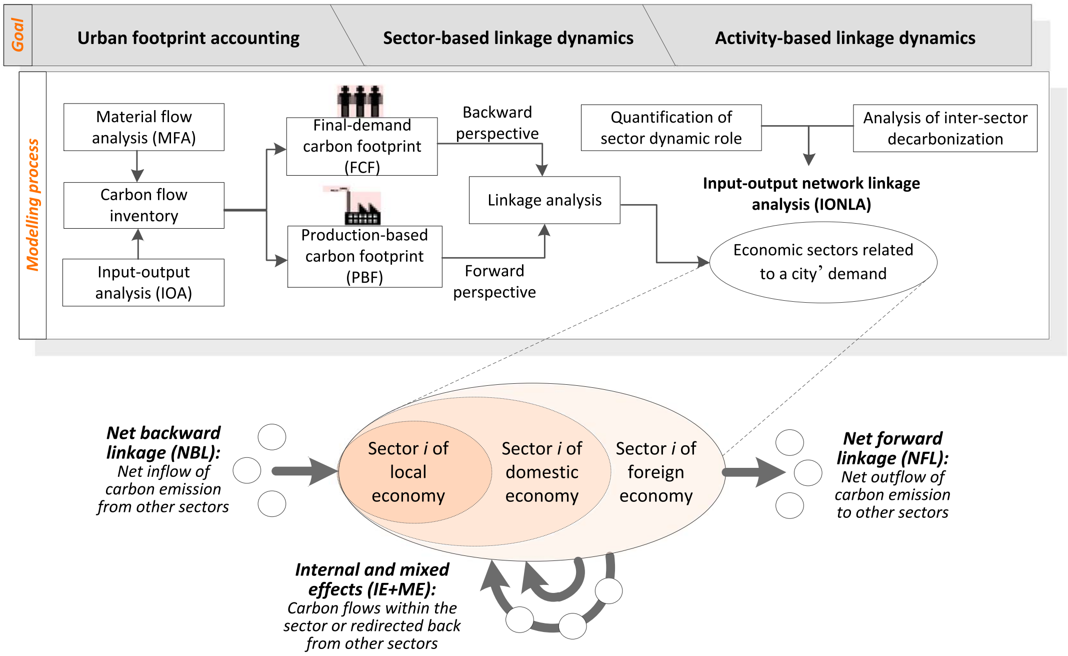


Figure 1. For modeling dynamic carbon linkages related to a city, a stepwise process is designated to perform input-output network linkage analysis.

with the improving resolution of input-output tables (Chen & Chen, 2016b; Minx et al., 2013). To compute embodied carbon emissions of a city, we use a MRIO to connect urban final demand with local, domestic, and global markets (Feng et al., 2013; Wiedmann et al., 2016). By doing so, not only are imports matched from different regions with their actual carbon intensities but also economic production structure is divided geographically to reflect trade across regions. A detailed description of this model is provided in the supporting information. The carbon emissions embodied in urban final demand originating from local production, domestic input, and international import are accounted for the following:

$$k_i = C_i / X_i \tag{1}$$

$$C^u_{\text{embodied}} = k^u_{1\times n}\left(I - A^u_{n\times n}\right)^{-1} y^u_{n\times 1} \tag{2}$$

$$C^d_{\text{embodied}} = k^d_{1\times mn}\left(I - A^d_{mn\times mn}\right)^{-1} y^d_{mn\times 1} - C^u_{\text{embodied}} \tag{3}$$

$$C^g_{\text{embodied}} = \sum\nolimits_{m'} k^g_{1\times(m+m')n}\left(I - A^g_{(m+m')n\times(m+m')n}\right)^{-1} y^g_{(m+m')n\times 1} - C^d_{\text{embodied}} - C^u_{\text{embodied}} \tag{4}$$

$$\begin{aligned} C^{\text{total}}_{\text{embodied}} &= \sum\nolimits_{m'} k^g_{1\times(m+m')n}\left(I - A^g_{(m+m')n\times(m+m')n}\right)^{-1} y^g_{(m+m')n\times 1} \\ &= C^u_{\text{embodied}} + C^d_{\text{embodied}} + C^g_{\text{embodied}} \end{aligned} \tag{5}$$

where n refers to the number of sectors, m refers to the number of domestic regions, and m' refers to the number of foreign regions. C_i is the total direct carbon emissions from Sector i (including those from energy use and industrial processes, as formulated in SI). X_i is the total output of Sector i; k_i is the carbon intensity of Sector i; Carbon intensity matrices are calculated based on the direct carbon emission inventory and total outputs of the local urban economy ($k^u_{1\times n}$), external regions within the domestic market ($k^d_{1\times mn}$), and foreign regions outside the country ($k^f_{1\times m'n}$); I is the identity matrix; $A^u_{n\times n}$ is the technology coefficient matrix of the local economy (only within the city); $A^d_{mn\times mn}$ is the technology coefficient matrix of the domestic regions (including the city), while $A^g_{(m+m')n\times(m+m')n}$ is the technology coefficient matrix of the global market (including the domestic regions); $(I\text{-}A)^{-1}$ is the Leontief inverse matrix (L). In the Leontief inverse matrix both direct and direct inputs to satisfy the unitary final demand in monetary value are captured (Leontief, 1951; Miller & Blair, 2009). $y^u_{n\times 1}$, $y^d_{mn\times 1}$, and $y^g_{(m+m')n\times 1}$ represent the final demand of the urban economy meet by local urban production, domestic input, and import, respectively; C^u_{embodied} is the carbon emission embodied in local production, C^d_{embodied} is the carbon emission embodied in domestic input, while C^g_{embodied} is the carbon emission embodied in international import; $C_{\text{embodied}}^{\text{total}}$ is the carbon emission embodied in the city's total final demand. All these variables are changed over time except I, which remains an identify matrix.

2.3. Disaggregate Analysis of Carbon Network Linkages

Based on the hypothetical extraction method in economic systems (Lenzen, 2003; Strassert, 1968), we quantify intersector linkages associated with carbon emissions by treating each economic sector as a block in the carbon flow network. Four types of linkages are formulated, including the internal linkage, mixed linkage, net forward linkage (NFL), and net backward linkage (NBL; Duarte et al., 2002; Sánchez-Chóliz & Duarte, 2005). The internal effect accounts for the carbon flows within a block (a sector in this case) and which is triggered by its own final demand; the mixed effect is the carbon flows from a block to other sectors, after which they reenter the original block to meet its final demand; the NBL is the external carbon flows that are used in a block to meet its final demand, that is, the net carbon import; the external forward linkage is the carbon emission originated from a block that is transferred to other sectors through trade, that is, the net carbon export. We modify the original one-scale (domestic economy) approach (Duarte et al., 2002; Sánchez-Chóliz & Duarte, 2005) into a three-scale input-output approach in which the contributions of urban (u), domestic (d), and global economy (g) to carbon linkages can be quantified separately

$$L = (I-A)^{-1} = \begin{bmatrix} \Delta_{i,i} & \Delta_{i,r} \\ \Delta_{r,i} & \Delta_{r,r} \end{bmatrix} \tag{6}$$

$$\text{internal linkages}\begin{cases} \mathrm{IE}^u = \widehat{k}^u \left(I-A_{i,i}^u\right)^{-1} y^u \\ \mathrm{IE}^d = \sum_m \widehat{k}^d \left(I-A_{i,i}^d\right)^{-1} y^d \mathrm{s}-\mathrm{IE}^u \\ \mathrm{IE}^g = \sum_{m'} \widehat{k}^g \left(I-A_{i,i}^g\right)^{-1} y^g-\mathrm{IE}^d-\mathrm{IE}^u \end{cases} \tag{7}$$

$$\text{mixed linkages}\begin{cases} \mathrm{ME}^u = \widehat{k}^u \left[\Delta_{i,i}^u-\left(I-A_{i,i}^u\right)^{-1}\right] y^u \\ \mathrm{ME}^d = \sum_m \widehat{k}^d \left[\Delta_{i,i}^d-\left(I-A_{i,i}^d\right)^{-1}\right] y^d-\mathrm{ME}^u \\ \mathrm{ME}^g = \sum_{m'} \widehat{k}^g \left[\Delta_{i,i}^g-\left(I-A_{i,i}^g\right)^{-1}\right] y^g-\mathrm{ME}^d-\mathrm{ME}^u \end{cases} \tag{8}$$

$$\text{net forward linkages}\begin{cases} \mathrm{NFL}^u = \widehat{k}^u \Delta_{(i,r)}^u y_r^u \\ \mathrm{NFL}^d = \sum_m \widehat{k}^d \Delta_{(i,r)}^d y_r^d-\mathrm{NFL}^u \\ \mathrm{NFL}^g = \sum_{m'} \widehat{k}^g \Delta_{(i,r)}^g y_r^g-\mathrm{NFL}^d-\mathrm{NFL}^u \end{cases} \tag{9}$$

$$\text{net backward linkages}\begin{cases} \mathrm{NBL}^u = k^u \Delta_{r,i}^u y^u \\ \mathrm{NBL}^d = \sum_m k^d \Delta_{r,i}^d y^d-\mathrm{NBL}^u \\ \mathrm{NBL}^g = \sum_{m'} k^g \Delta_{(r,j)}^g y^g-\mathrm{NBL}^d-\mathrm{NBL}^u \end{cases} \tag{10}$$

$$\mathrm{NL} = \sum_{i=1} \mathrm{NBL}_i = \sum_{i=1} \mathrm{NFL}_i \tag{11}$$

where Δ refers to the Leontief inverse (L) divided by blocks in the economy, for example, $\Delta_{i,\ i}$ represents the block within Sector i, $\Delta_{r,\ i}$ represents the block (column) from the rest of the network to Sector i, $\Delta_{i,\ r}$ represents the block (row) from Sector i to the rest of the network, and $\Delta_{r,\ r}$ represents the block between the rest of the network (with Sector i left out). The technology coefficient matrices are directly derived from the urban single-region input-output table (A^u), domestic multiregion input-output table (A^d), and global multiregion input-output table (A^f). The final demand associated with the production in local urban area (u), domestic regions (d), and global regions (g) is defined as y^u, y^d, and y^g. With the aggregation of geographically distributed linkage networks, carbon linkage networks induced by domestic and foreign economy can be displayed in the same sector format with the urban linkage network. NL is the amount of total net carbon linkage related to a city (either summing all the NFLs or summing all the NBLs), which is total carbon inflows or outflows of sectors excluding those originating within them.

2.4. Indicators for Network Linkage Analysis

Linkage analysis is used to reveal what is included in consumption- and production-based accounting perspectives. Final consumption carbon footprint (FCF_i) covers the carbon emissions in local and upstream supply chains that are triggered by sector *i*'s final demand (including residential consumption, capital formation, and export). FCF can be decomposed into internal and mixed linkages plus NBLs. In comparison, production-based carbon footprint (PBF_i) covers both local and upstream requirements to support all production activities in sector *i*, which is composed of internal (IE) and mixed linkages (ME) plus NFL

$$\text{sectoral footprints}\begin{cases}\mathrm{FCF}_i\equiv\mathrm{IE}_i+\mathrm{ME}_i+\mathrm{NBL}_i\\ \mathrm{PBF}_i\equiv\mathrm{IE}_i+\mathrm{ME}_i+\mathrm{NFL}_i\\ \Delta C_i=\mathrm{PBF}_i-\mathrm{FCF}_i=\mathrm{NFL}_i-\mathrm{NBL}_i\end{cases}\tag{12}$$

where each linkage in the above equations should be interpreted as the one originated from various sources, in line with the previous decomposed calculation of the carbon flows. For example, IE_i can be treated as the internal linkages of Sector *i* associated with local production, domestic input, or international import. FCF_i and PBF_i are final consumption-based and production-based carbon footprints of sector *i*. The inclusion of linkages in sectoral footprints is demonstrated in Figure 2.

The difference between FCF_i and PBF_i lies in the difference between the backward and forward linkages of Sector *i* (ΔC_i). The difference between NBL and NFL reflects the different roles sector play in transferring carbon emission. If $\Delta C_i > 0$, Sector *i* is a net carbon supplier in the network (causing carbon emissions elsewhere), while $\Delta C_i < 0$ indicates Sector *i* is a net carbon importer (driving carbon emissions from its import). Further, the total city-wide FCF and PBF are also formulated by summing up all the carbon emissions associated with all economic sectors

$$\text{urban footprints}\begin{cases}\mathrm{FCF}_{\mathrm{total}}\equiv\sum_j^n\mathrm{FCBF}_j\\ \mathrm{PBF}_{\mathrm{total}}\equiv\sum_i^n\mathrm{FPBF}_i\\ \mathrm{FCF}_{\mathrm{total}}=\mathrm{PBF}_{\mathrm{total}}\end{cases}\tag{13}$$

where the sum of all economic sectors' FCFs ($\mathrm{FCF}_{\mathrm{total}}$) equals the sum of their PBFs ($\mathrm{PBF}_{\mathrm{total}}$) since all the carbon emissions embodied in inputs of products and services are triggered by final demands of urban economy (household and government consumption, capital formation, and export).

Various approaches have been proposed to quantify linkages that are driven by one sector bidirectionally, including unweighted (Lenzen, 2003) and weighted (Cazcarro et al., 2010) indices on forward and backward linkages in monetary and physical terms. However, the actual change in the role each sector plays in the context of whole economy has not been fully reflected in these indices. Here we developed a normalized indicator called role switching speed (α), a nondimensional metric identifying how a sector's role is changing over time. It denotes the relative difference between the evolution of a sector and the development of the whole economy.

$$\alpha_i\equiv\frac{n\Delta l_i}{\Delta\sum l_i}=\frac{n\left(l_i^t-l_i^{t-1}\right)}{\sum_{i=1}^n l_i^t-\sum_{i=1}^n l_i^{t-1}}\tag{14}$$

in which carbon linkage (l) can be internal and mixed effect linkages, NBL or NFL. The assessment of role

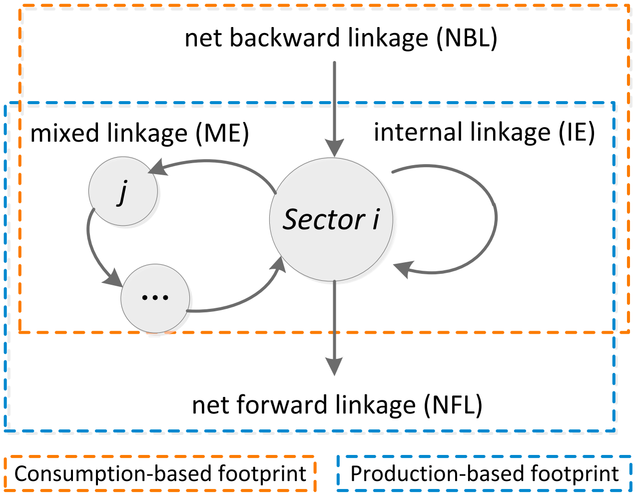


Figure 2. A demonstrative diagram for the inclusion of linkages in sectoral footprints.

switching is based on the comparison between two points in time, that is, t and $t-1$. Three situations emerge based on the α value given a positive change in $\Delta \sum l_i$: (1) fast increasing role (>1), (2) slowly increasing role (0 < <1), and (3) decreasing role (<0). See detailed explanation of role identification in SI.

There are a number of systems metrics that describe intersector relationships in a network such as control analysis (Fath, 2004; Hines et al., 2016; Patten & Auble, 1981; Schramski et al., 2006). Alternatively, we developed an indicator called net linkage contribution (β), which describes the contribution of linkages associated with a certain sector to the whole urban carbon network. β is a nondimensional index identifying the most active and dominant carbon linkages that transfer carbon emissions among sectors. The disaggregated analysis at activity level is important for optimizing industrial activities related the urban economy and adjusting intersector carbon flows across urban boundary.

$$\beta_{ij} = \frac{nl_{ij}}{\mathrm{TCT}'} \times 100\% \tag{15}$$

where nl_{ij} refers to net linkage between Sectors i and j (excluding internal and mixed linkages); TCT′ refers to total carbon throughflow without initial and cycling flows, that is, the sum of all net carbon linkages in the urban economy (intersector $n \times n$ matrices). β_{ij} can be interpreted as the importance of an intersector linkage in the carbon networks induced by local production, domestic input, and international import.

We applied this model to Beijing in the years 1990–2012 to explore changes in carbon emission linkages over time, focusing specifically on the new parameters. A description of the case city (Beijing) and the data used for IONLA is provided in SI.

3. Results

3.1. Transfer of Total Carbon Linkages Over Time

The total net carbon linkages (NL) increased from 27 to 237 Mt CO_2, while internal and mixed effect linkages increased from 79 to 400 Mt CO_2 (Figure 3). For these two linkages, the proportion of local production has decreased from 82% to 39% over 1990–2012 and the major contribution has switched to domestic and foreign regions. Similarly, the role of external production has been a dominant fraction of total net carbon linkages with a change from 12% to 56% over 1990–2012. This indicates that although local production has remained important, production in domestic China and foreign regions has increasingly contributed to carbon emissions of Beijing. The total embodied carbon emissions of Beijing from 1990 to 2012 rise constantly whether originating from local production, domestic input, or import, resulting in a total increase from 106 to 637 Mt CO_2 (Figure S1). The disaggregated results showed asynchronous carbonization among different economic sectors (Figures S2–S4). Some economic sectors have been rapidly externalizing their carbon footprint to sectors in other regions. For manufacturing sectors, 65–78% of the carbon flows among petroleum processing and coking (S9), chemicals (S10), nonmetal mineral products (S11), and smelting and pressing of ferrous and nonferrous metals (S12) are induced by domestic input, whereas 9–15% of these flows are from imports due to the global labor division in 2012. Over 94% of the carbon footprint of coal mining, petroleum, and natural gas extraction (56 Mt) is attributed to domestic input and import, and this increase is much higher than that from local production.

3.2. Dynamic Carbon Linkages at Sector Level

A major transition in urban carbon linkages is shown at the sector level (Figure 4). In total, carbon linkages produced within and among economic sectors in 2012 increased by 780% and 406%, respectively, compared with the level in 1990. A drastic increase of urban carbon linkages occurred in 2005, after which domestic input and foreign import began to have a strong impact on carbon linkages either within or among sectors (Figure S5).

For some economic sectors, major carbon leakage mainly occurred mainly from internal production. We found that 47% of the production-based footprint of electricity, gas, and hot water in Beijing happened in other regions in 2012, higher than its proportion (39%) in 1990. NFL associated with this sector increased by 750% (from 4 Mt in 1990 to 39 Mt in 2012), due to increasing reliance of the energy supply on domestic and global markets. This transition also occurred in the agriculture (S1) and manufacturing sectors, such as ferrous and nonferrous metals mining and dressing (S3) and nonmetal minerals mining and dressing

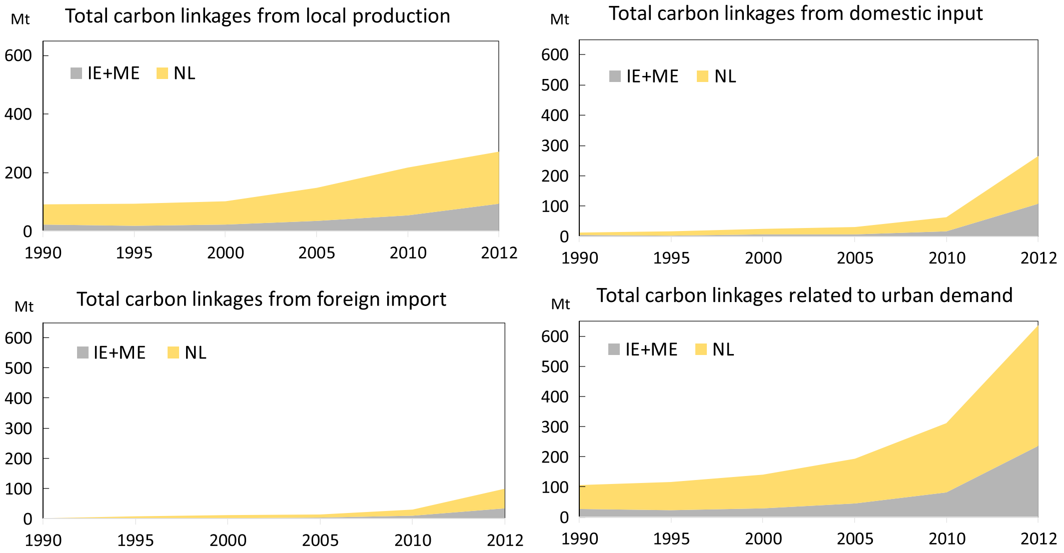


Figure 3. Although local activities have remained an important part, production in other provinces in China and foreign regions has an increasingly big contribution to the carbon linkages of Beijing. Note: Total net carbon linkage (NL) related to a city is either the total of all net forward linkages or all the net forward linkages; IE + ME sums up the internal and mixed effect of carbon linkages. IE = internal linkage; ME = mixed linkages.

(S4). The growth of production-based footprints of these three sectors is mainly due to their increased proportions of NFLs induced by domestic input and import (an increment of 60%, 22%, and 72% for S1, S3, and S4). Second, for some other sectors, major carbon leakage was observed mainly due to increase in consumption. For example, the increase in consumption-based footprint of food processing and production (S5), textile industry (S6), and equipment-related sectors (S14–S17) was mainly due to their net backward carbon linkages. Some sectors have significant increases in both production- and consumption-based footprints. Coal mining, petroleum, and natural gas extraction (S2); petroleum processing and coking (S9); and chemicals (S10) outsourced over 70% of their carbon linkages to domestic and global regions in 2012, much higher than that in 1990. For these sectors, the reallocation of both internal and external linkages contributed greatly to total dynamics of city-driven carbon flows.

We find an uneven change in the role sectors play in manipulating carbon emission linkages (Figure 5). Services sectors (S21–S24) and construction sector (S20) have been increasing their role with more intensive internal plus mixed linkages and NBL compared to average change in the urban economy. The "self-supply" and "external-supply" activities in these sectors triggered a rapid increase in their embodied carbon flows. It is clear that 1995–2000 was an important time frame for role switching in these sectors, especially for the carbon linkages induced within urban territory. On the other hand, the demand of several heavy industries (S9–S12) in Beijing has been met by the supply from domestic and foreign regions that are less populated or less expensive. This is reflected by the increasing roles of these sectors in producing internal and mixed effect linkages and net forward carbon linkages over time. For these manufacturing sectors 2005–2010 is a significant interval in time for carbon emission linkage to change.

3.3. Dynamic Carbon Linkages at Activity Level

Beijing's internal carbon linkages were also dynamic over time (Figure 6). There has been great diversity in Beijing's net intersector carbon linkages over time, from either the backward or forward perspectives. While carbon emissions allocated among sectors have notably shifted over the period 1990–2012, some sectors remain dominant over others in creating carbon linkages.

From the backward perspective, the Construction sector (S20) is one of the largest sectors in attracting carbon linkages and thus causing carbon leakage in the city. The flows from nonmetal mineral products (S11) and smelting and pressing of ferrous and nonferrous metals (S12) to construction are one of the biggest net carbon linkages in the networks and have been growing fast with time. Fast expansion of housing and construction of public infrastructure resulted in large net linkages from S11 to S20 (10 Mt) and from S12 to S20

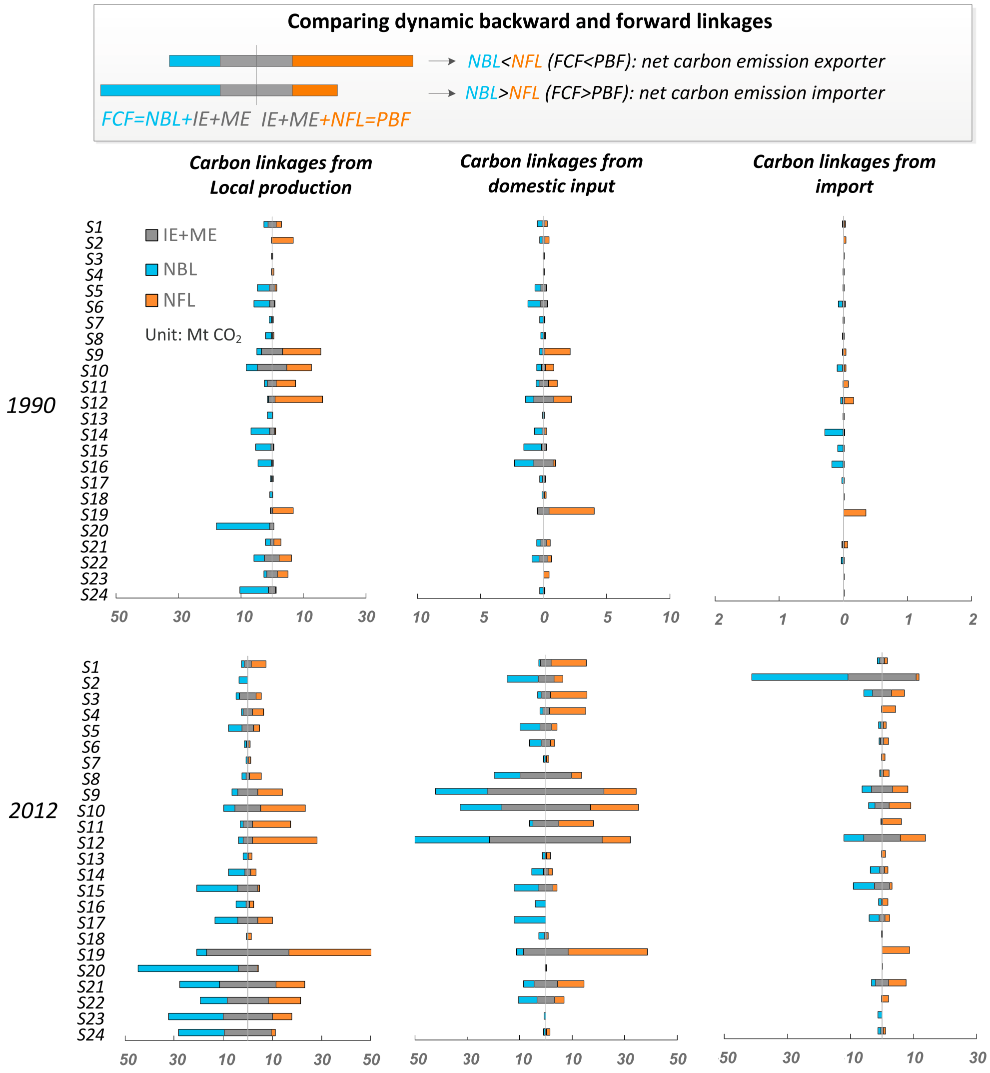


Figure 4. Comparison of carbon linkages from local production, domestic input, and international import between 1990 and 2012 shows that for some economic sectors, major carbon leakage occurred mainly from local production, whereas for other sectors, major carbon leakage was due to consumption of imported material. Results in other years are provided in Figure S5. The 24 economic sectors in the figure are as follows: S1: agriculture; S2: coal mining, petroleum, and natural gas extraction; S3: ferrous and nonferrous metals mining and dressing; S4: nonmetal minerals mining and dressing; S5: food processing and production; S6: textile industry, garments, and other fiber products and leather, furs, down, and related products; S7: timber processing, bamboo, cane, palm fiber, and straw products and furniture manufacturing; S8: papermaking and paper products and printing and record medium reproduction; S9: petroleum processing and coking; s10: chemicals; S11: nonmetal mineral products; S12: smelting and pressing of ferrous and nonferrous metals; S13: metal products; S14: ordinary and special machinery and equipment; S15: transportation equipment; S16: electric equipment and machinery; S17: electronic and telecommunications equipment, instruments, meters, cultural, and office machinery; S18: other manufacturing industry; S19: electricity, gas, and hot water; S20: construction; S21: transportation, storage, post, and telecommunication services; S22: wholesale, retail trade and catering services, and restaurant and renting; S23: finance, insurance, scientific, and environmental and technical services; and S24: public services and others services. NBL = Net backward linkage; NFL = net forward linkage; FCF = final consumption carbon footprint; PBF = production-based carbon footprint; IE = internal linkage; ME = mixed linkage.

(9 Mt) in 2012, which doubled the level in 1990. The increased energy consumption for construction also resulted in a significant linkage from electricity, gas, and hot water to construction (6 Mt) in 2012. Transportation (S21) and services sectors (S22–S24) have driven carbon linkages from the energy supply sector (S19) due to their growing consumption of fossil fuels and electricity since 1990.

From the forward perspective, we found that the most intensive carbon linkages have been driven by petroleum processing and coking (S9), chemicals (S10), smelting and pressing of ferrous and nonferrous metals (S12), and electricity, gas, and hot water (S19). This domination of forward linkage has not changed over

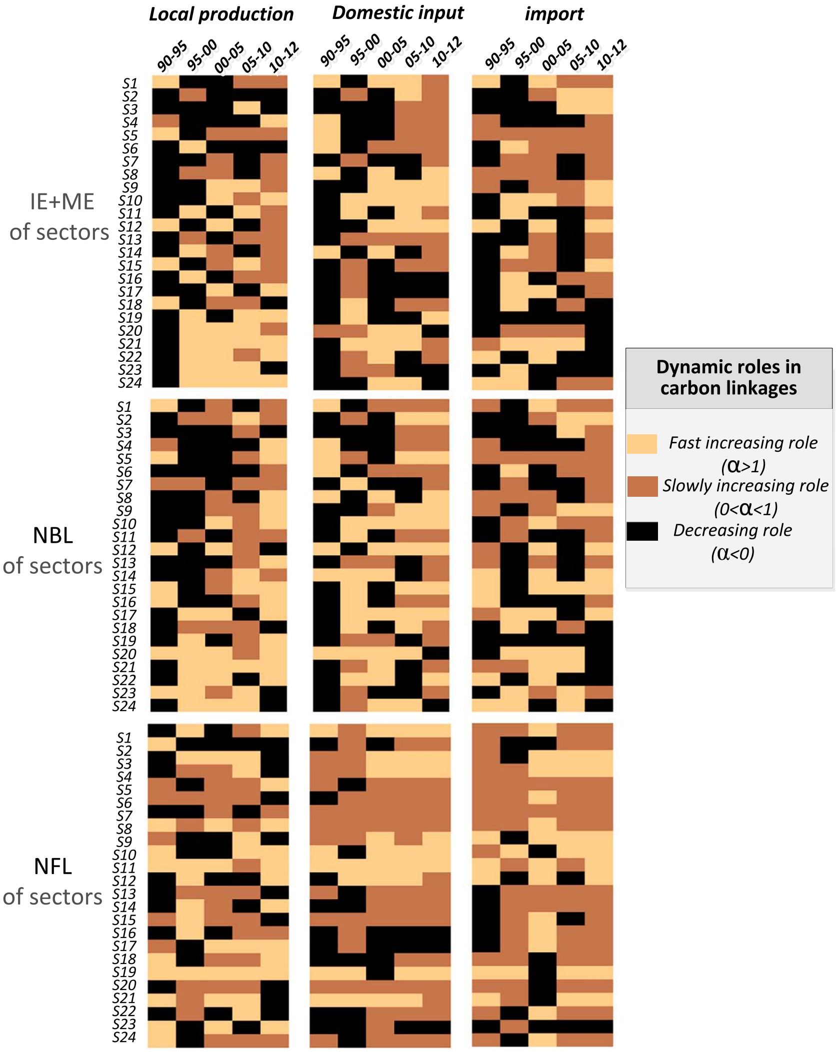


Figure 5. Major change in sectors' roles is found from the dynamics of carbon linkages from local production, domestic input, and international import. Note: A full presentation of the dynamics in all types of carbon linkages from local production, domestic input, and import is provided in Tables S3–S5. IE = internal linkage; ME = mixed linkage; NFL = net forward linkage.

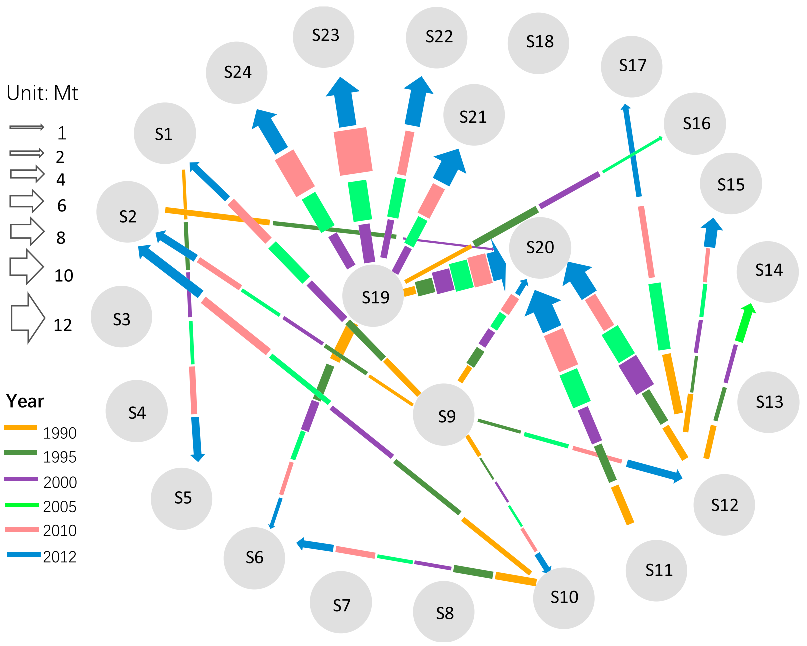
the last two decades, which indicates these sectors are essential in supplying energy or other fundamental resources for urban growth. The carbon linkage between S19 and S20 increased by 350% from 1990 to 2012, while the equipment-related sectors (such as S15 and S16) also increased by 400%. The linkage from energy supply to transportation has become an important carbon linkage since 2000. Services sectors (S22–S24) also came to play a significant role in creating urban carbon linkages in 2000, when the linkages from energy supply to services sectors began to increase. In 2012 these linkages declined by about 10–20% compared to the level in 2010. The improved energy efficiency in production within or outside the urban boundary accounts for the recent decarbonization of these services sectors.

4. Discussion and Conclusions

This work develops an integrated approach (IONLA) to identify and quantify the dynamic of carbon emission linkages associated with various economic sectors and metabolic activities. The main findings and insights of this study are as follows:

1. We find a clear trend of carbon leakage associated with the Beijing urban economy over time. On one hand, the total consumption-based footprint of Beijing has increased by five times from 1990 to 2012

(a) Net carbon linkages from 1990 to 2000 (in Mt CO_2)



(b) Most dominant inter-sector net linkages (in β value)

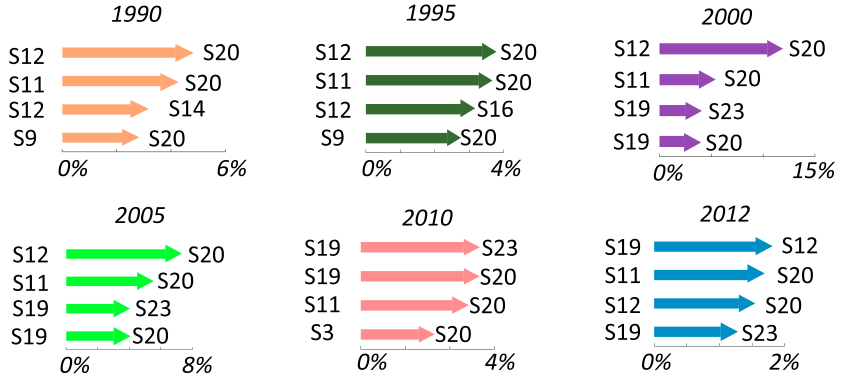


Figure 6. (a, b) While carbon emissions allocated among sectors have notably shifted over the period 1990–2012, some sectors (such as construction, petroleum processing and coking, chemicals, smelting and pressing of ferrous and nonferrous metals and electricity, gas, and hot water) remain dominant over others in creating carbon linkage. Note: Only the linkages contributing higher than 1% to the total carbon throughflow (the sum of all net carbon linkages) were shown in this figure.

as a result of rapid urbanization. Growth in per capita consumption is one of the major reasons for the recent drastic increase in the carbon footprint. On the other hand, global cities such as Beijing outsource a huge amount of carbon to their “hinterlands” via trade. It was reported that over 30% of Beijing's final consumption-driven carbon emissions were externalized to other regions in 2007 (Chen et al., 2013; Shao et al., 2016). The trend of externalizing production chains and carbon emissions will probably continue during globalization. This poses a major challenge for carbon mitigation by local governments. A viable solution would be a cooperation between cities and their trade partners in low-carbon industries and business.

2. We acquire important details of the city's changing carbon footprint via the dynamics of carbon emission linkages. Through dynamic IONLA, we can identify when and in which sector the changes of carbon linkages are most prominent. For the case of Beijing, 1995–2000 was an important period for services and

construction sectors regarding role switching in carbon flows, while 2005–2010 was a significant interval for these manufacturing sectors. With the help of a new indicator, that is, role identification (α), a standardized comparison of linkages between single sectors and the whole economy over time provided a fairer judgment of the role each sector plays in carbon footprints. Applying a network approach to input-output linkage analysis, net linkage contribution (β) provides a transparent analysis and visualization on the starting and destination sectors associated with each single linkage. The difference between consumption-based footprint and production-based footprint can be clearly interpreted by net intersector carbon linkages. For Beijing, a large consumption-based footprint in the construction sector is mainly due to the fast-growing backward linkages from other sectors. The linkages from nonmetal mineral products, smelting, and pressing of ferrous and nonferrous metals to construction sector are among the biggest net carbon linkages over time due to the high demand of housing and construction of public infrastructure. The net linkages of the energy sector to services sectors remain important in Beijing's local economy (especially after 2010) even their emission intensity has gone down. The fast-growing services sectors, with increasing backward linkages, should be the new focus of emission cutting inside the city. The manufacturing-related net linkages have been increasingly transferred outside the city since 2005. But reallocating heavy industries elsewhere is not a systemic solution for carbon footprint mitigation. Targeting key sectors and processes and finding an economic and socially acceptable way of mitigating carbon emissions across boundaries are ideal options. Local governments should financially privilege the companies that employ clean and low-carbon products, either from local production or import. Moreover, cities should collaborate with their close economic and trade partners to optimize the whole supply chains.

3. The limitations of this analysis include a number of aspects. First, input-output analysis assumes the homogeneity of activities within a sector, which could lead to uncertainties in delineating activities of the economy. Also, the production technology of a sector is often assumed to be constant in the technical structure. Second, all MRIO databases have uncertainties to some extent. China publishes MRIO tables regularly for Beijing and other provinces/cities. For many other cities, the lack of urban input-output tables hampers the IONLA or similar analyses. Fortunately, a range of studies has been devoted to connecting an urban economy to the MRIO tables for urban carbon footprint calculations (Hermannsson & McIntyre, 2014; Hu et al., 2016; Wiedmann et al., 2016), hopefully making the carbon linkages modeling easier at city level. The MRIO tables from the World Input-Output Database have more comprehensive environmental data but only cover 43 major countries in the world (other regions are characterized as "rest of the world"). Life cycle analysis is an alternative approach for environmental footprinting, although it requires city-scale metabolic data, which are often rare (some exceptions in Ramaswami et al., 2008; Goldstein et al., 2013). Finally, the fossil fuels directly combusted in households (e.g., during cooking or commuting) are not included in final consumption carbon emission due to a lack of accurate data, and the carbon emission linkages only relate to local and upstream production activities.

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