Carbon Emission Drivers and Critical Paths in the Interaction of the "Local-Domestic-International" Economic Cycle - A case study of Beijing

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Abstract

It is crucial to study the carbon emissions worldwide induced by urban consumption activities. Taking consumption-oriented city Beijing as an example, we constructed a nested multi-regional input-output model (MRIO), and measured carbon emissions and value-added in local, domestic, and international systems. Furthermore, the structural decomposition analysis (SDA) and structural path analysis (SPA) was applied to analyze cross-system driving forces and key paths of carbon emission changes. The conclusions show: (1) Beijing's consumption leads to the highest carbon emissions in the domestic system but the highest value-added in the local system. There is spatial inconsistency in carbon emissions and value-added. (2) The intermediate commodity input-output effect (ICIOE) of intra-domestic provinces is the main driving factors contributing to the reduction of carbon emissions. In contrast, the ICIOE of inter-domestic provinces is the main factor leading to the rise. (3) In the top 10 types of key paths for Beijing's consumption-based carbon emissions (CBCE) growth, electric power and construction sectors in domestic systems are key sectors. Chemical products and transport equipment in foreign systems are key sectors for Beijing's CBCE decrease. Our findings suggest Beijing enhancing cross-system cooperation to achieve carbon reduction targets.

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1. Introduction

In order to give full play to the advantages of China's mega-market, the Chinese government proposed building a new development paradigm featuring dual circulation, including domestic and international. In addition to this, the economic cycles of local systems cannot be ignored, especially in typical cities (Chen et al., 2022). Through frequent trade activities, cities import large quantities goods from domestic and international regions, it is therefore necessary to examine trade linkages among "Local-Domestic-International" systems.

Rapid economic growth has brought about serious environmental pollution while facilitating domestic and foreign trade (IEA, 2010; Kong et al., 2023). Over 70% of greenhouse gas (GHG) worldwide are caused by urban economic activities (Elmqvist et al., 2019). Climate change is a global issue (Chen et al., 2022; Zhu et al., 2022), and to achieve the global goal of net zero emissions, cities must consider the carbon emissions of other economic systems caused by their consumption. Therefore, studying cross-system consumption-based carbon emissions (CBCE) of cities can recognize its driving effect on global carbon emissions. This will provide a theoretical basis for cooperation in combating climate change and formulating international carbon reduction strategies.

Clarifying the driving factors and key paths of CBCE is of significance for the scientific formulation of carbon emission reduction policies. MRIO can reflect cross-system industry linkages (Zheng et al., 2022). The SDA has been commonly applied to analyze driving factors of CBCE combined with MRIO (Liu et al., 2015; Mi et al., 2017; Pan et al., 2018; Radwan et al., 2022; Pang et al., 2023). Previous studies mainly investigated the impact of three influencing factors, including CO_2 intensity effect, intermediate commodity IO effect (ICIOE), and final demand effect (Zhang et al., 2020; Zheng et al., 2020; Su et al., 2022; Liu et al., 2023). For the intermediate commodity IO effect, most studies consider the Leontief inverse matrix as a whole and do not decompose it in detail (production structure, the Leontief structure effect and IO technology effect), while Peng et al. (2015) decompose it into five factors due to the consideration of industrial linkages between domestic and international systems, few studies decompose it among "Local-Domestic-International" three-level systems.

Studies using SDA cannot identify critical intermediate transactions in supply chains or reflect the effects of the sectoral connection on carbon emissions (Li et al., 2020). Structural path analysis (SPA) can make up for this shortcoming. SPA initially focused on economic issues (Lantner, 1972; Crama et al., 1984) and then extended to the environmental fields (Lenzen, 2003). SPA can decompose a specific industry's resource consumption or environmental emissions into infinite flow pathways between industries (Lenzen and Murray, 2010; Nagashima et al., 2018; Su et al., 2019; Li et al., 2020). Many scholars have investigated critical paths of CO_2 emissions in China, Australia, and India (Liang et al., 2014; Li et al., 2018; Zhang et al., 2020; Zhang et al., 2021; Chen et al., 2022; Wang et al., 2023). Existing studies mainly identified critical paths for resource and environmental emissions

within a certain country or a specific region, few studies consider cross-system critical paths, which is important for multi-system cooperation in developing carbon reduction strategies.

To fill the above gaps, we use the example of Beijing to examine the cross-system driving factors and key paths of its CO_2 emission changes, with a view to providing reference for cross-system realization of carbon emission reductions.

Beijing is chosen as a case to be analyzed for the following three reasons. (1) Beijing is a consumer center (Kong et al., 2021). The contribution of final consumption expenditure to Beijing's economic growth reached 60.1% in 2021 (Beijing Municipal Bureau of Statistics, 2023). The Evaluation Report on International Consumer Centre Cities in 2021, released by the 21st Century Institute of Economic Research, indicated that Beijing surpassed Shanghai to become the most powerful city in China (21st Century Institute of Economic Research, 2023). Robust consumer demand generates large carbon emissions, and roughly 90% of Beijing's carbon footprint was attributed to other Chinese and international regions in 2012 (Shao et al., 2016). (2) Beijing's participation in domestic and international trade is high. As an international metropolis, Beijing occupies a critical position in both domestic and international economic system (Wang et al., 2023). In the first half of 2023, Beijing's import and export value totaled 1.79 trillion yuan, year-on-year growth of 5.9%, higher than the national growth rate of 3.8 pp. (3) Beijing is the capital of a developing country, and its carbon reduction potential is much greater than that of a developed country's metropolis (IRP, 2020). Beijing influences key carbon emission paths by altering trade partners domestically and internationally, reshaping the global carbon emission network and further bringing about dramatic changes to the CO_2 emission pattern in China and globally. Beijing's carbon emission reduction strategy has implications for other developing country capitals.

This paper is organized around the following areas using the example of Beijing, the capital of a developing country. (1) How much carbon emissions are generated locally, domestically, and internationally due to Beijing's participation in the domestic and international trade on consumption-based? (2) What are the driving factors of CO_2 emission changes on the consumption-based involving different systems? (3) What are the key paths of CO_2 emission changes on the consumption-based across the local, domestic, and international systems? The marginal contributions of our study are twofold. First, we further decompose the Leontief inverse matrix into 11 factors by considering forward and backward industry linkages of three systems (Figure 1), which deepens research methods of factors influencing CBCE changes. Second, most of the studies that have been done have implemented SPA within a particular system, we use SPA to identify key paths of Beijing's CBCE changes across "Local-Domestic-International" systems, integrating domestic provinces and foreign countries into one analytical framework, expanding the research scale.
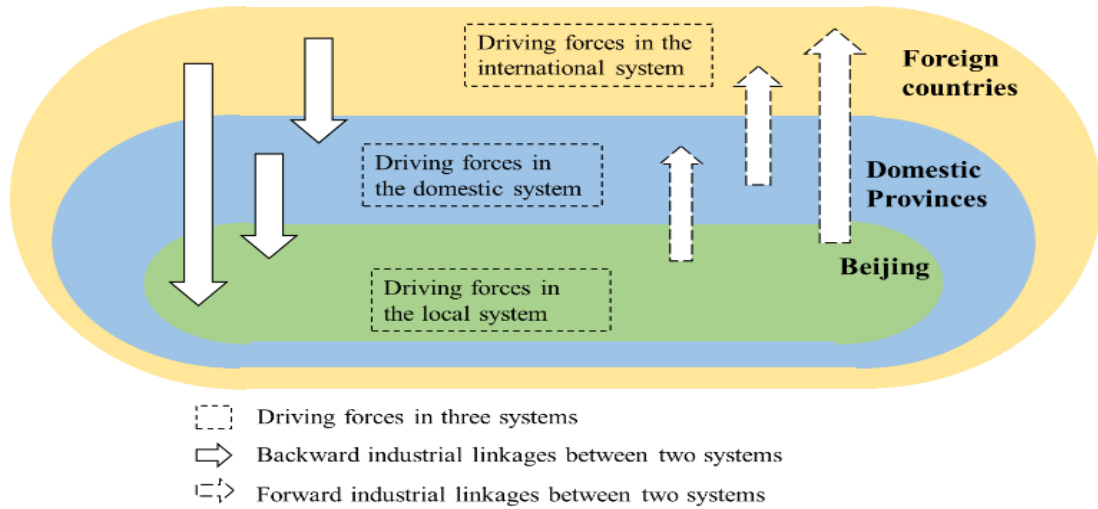
Figure 1: Decompose L into 11 factors involving three systems

2. Methods and data

2.1 "Local-Domestic-International" nested input–output analysis

To analyze Beijing's economic linkages with domestic provinces and foreign countries, China's MRIO table (CMRIO) was nested in the world input–output table (IOT) in 2012 and 2017. According to existing nested schemes (Fry et al., 2022), a three-level nested multi-regional input–output (MRIO) model was constructed, comprising Beijing, 30 other provinces in China and 43 countries and regions worldwide, as shown in Figure 2. In the nested economic system, Beijing is linked to local, domestic, and foreign systems, denoted by B, D and F, respectively. Z is the matrix of intermediate product flows; Y is the final demand matrix. The subscript rs (r, s=B, D and F) indicates the products supplied by region r to region s.

Figure 2: "Local-Domestic-International" nested MRIO

The constant coefficient assumption was referenced in the nesting process (Jiang et al., 2022). According to the structure of China's imports and exports in the input–output (IOT), the imports and exports of each province in CMRIO were assigned to each country. The total inputs and outputs were then adjusted to balance the nested MRIO.

Taking the example of sector i in Beijing export to sector j in country F, the nested formula of Z is as follows.

$$Z_{B,F}^{I,j} = \frac{Z_{CN,F}^{I,j}}{Z_{CN}^{i}} Z_{B}^{I}$$
(1)

Here, $Z_{B,F}^{I,j}$ is the output or services exported from sector i in Beijing to sector j in a foreign country after nesting. $Z_{CN,F}^{I,j}$ is the output or services exported from sector i in China to sector j in a foreign country in the IOT. CN denotes China in the IOT. Z_{CN}^{I} represents total exports from sector i in China in the IOT, and Z_{B}^{I} represents total exports from sector i in Beijing in the CMRIO.

The environmentally extended MRIO (EE-MRIO) can describe the economic linkages and show information on cross-system environmental emission. We constructed an EE-MRIO table by placing the carbon emission accounts attached to CMRIO and IOT below the three-level nested MRIO table.

2.2   Accounting for CBCE in "Local-Domestic-International" systems

This paper defines Beijing's consumption-based carbon emissions (TCE_B) as carbon emissions generated in three systems induced by Beijing's final demand. Based on the three-level nested EE-MRIO built in 3.1, the total input–output balance equation follows.

$$X = (I-A)^{-1}Y = LY$$
(2)

To calculate TCE_B, the matrix $\hat{c}$ was introduced.

$$\widehat{C} = \begin{bmatrix} c_B & 0 & 0 \\ 0 & c_D & 0 \\ 0 & 0 & c_F \end{bmatrix}$$
(3)

Elements in $\hat{c}$ (c_B, c_D, c_F) indicate direct carbon emission intensity, which is the ratio of C (CO_2 emission of each region) to X. Then, we obtain the TCE_B.

$$TCE_B = \hat{c}LY_B$$
(4)

By expanding Equation (3),

$$\text{TCE}_B = \begin{bmatrix} \text{TCE}_{BB} \\ \text{TCE}_{DB} \\ \text{TCE}_{FB} \end{bmatrix} = \begin{bmatrix} c_B \sum_{t=B,D,F} L_{Bt} Y_{tB} \\ c_D \sum_{t=B,D,F} L_{Dt} Y_{tB} \\ c_F \sum_{t=B,D,F} L_{Ft} Y_{tB} \end{bmatrix} \tag{5}$$

TCE_B is equal to the sum of the first column elements in the matrix of Equation (5). TCE_{BB} denotes the carbon emissions in the local system. TCE_{DB} denotes the carbon emissions in the domestic system. TCE_{FB} denotes the carbon emissions in the international system (Figure 3).
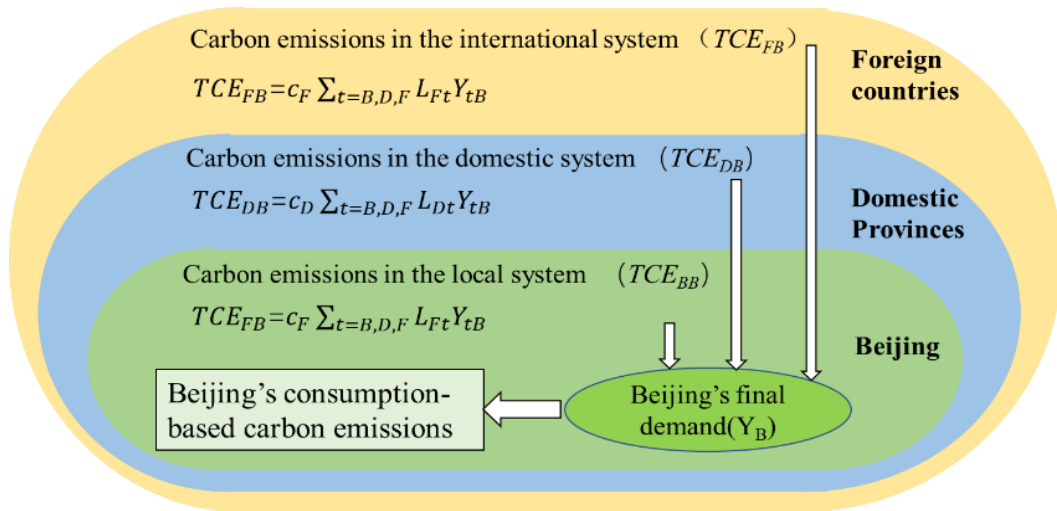

Figure 3: Accounting for Beijing's consumption–based carbon emissions

Economic activities cause carbon emissions, and it is reasonable to consider the corresponding value–added benefits while analysing CO_2 emissions problems. Replacing $\widehat{C}$ with $\widehat{V}$, we obtained the value–added that Beijing's final demand created in three systems (TVA_B). Elements in $\hat{v}$ is the ratio of V (value-added of each region) to X. See Appendix 1 for details.

2.3   SDA of CBCE changes involving "Local-Domestic-International" systems

SDA is commonly applied to identify driving factors of environmental problems, particularly those related to CO_2 (Naspolini et al., 2020; Jiang et al., 2021).

This paper adopted SDA to clarify the causes of changes in TCE_B. Beijing's final demand vector Y_B can be expressed as $Y_B = P_B S_B K_B$ (Peng et al., 2015). P_B is the commodity structure of final demand, S_B is the spatial structure of final demand and K_B is the consumption scale of final demand. Formula (4) can be written as

$TCE_B = \hat{c}LP_BS_BK_B$. From 2012 (period 0) to 2017 (period 1), the change of TCE_B is shown in Equation (6).

$$\Delta TCE_B = c^1L^1P_B^1S_B^1K_B^1 - c^0L^0P_B^0S_B^0K_B^0 \tag{6}$$

Equation (6) can be decomposed as follows:

$$\Delta TCE_B = CE(\Delta c) + CE(\Delta L) + CE(\Delta P_B) + CE(\Delta S_B) + CE(\Delta K_B) \tag{7}$$

Here, $CE(\Delta c)$ is carbon intensity effect, and $CE(\Delta L)$ is the intermediate commodity input–output effect. We used the bipolar decomposition method suggested by Dietzenbacher and Los (1998) because it generates fewer errors than other methods (Gu and Lv, 2016).

Furthermore, from $L = (I-A)^{-1}$ we obtain the following equation:

$$\Delta L = L^1 - L^0 = L^1 \Delta A L^0 \tag{8}$$

The L matrix contains both input–output relationships within and between three systems, so it must be decomposed further. A was decomposed into 11 factors based on Peng et al. (2015), which decomposed into five factors. Appendix 2 presents the processing steps and specific meanings.

Thus, ΔA can be written as Equation (9).

$$\Delta A = \Delta A_{BB}^* + \Delta A_{-BD}^* + \Delta A_{-BF}^* + \Delta A_{DB}^* + \Delta A_{FB}^* + \Delta A_{BD}^* + \Delta A_{BF}^* + \Delta A_{DD}^* + \Delta A_{FF}^* + \Delta A_{DF}^* + \Delta A_{FD}^*$$

$$\tag{9}$$

Moreover, the carbon emission intensity $c = c_B^* + c_D^* + c_F^*$. Of which, $c_B^* = (c_B, 0, 0)$, $c_D^* = (0, c_D, 0)$, $c_F^* = (0, 0, c_F)$. Therefore, the change in CO_2 emission intensity was decomposed as follows: $\Delta c = \Delta c_B^* + \Delta c_D^* + \Delta c_F^*$.

Overall, the change of TCE_B can be decomposed into the sum of 17 factors, shown in Table 1.

Table 1: Factors influencing the change of TCE_B

	Influencing factors	Implications
Carbon intensity effect	$CE(\Delta c_B^*)$	Local
	$CE(\Delta c_D^*)$	Domestic
	$CE(\Delta c_F^*)$	International
Intermediate commodity input-output effect	$CE(\Delta A_{BB}^*)$	Local
	$CE(\Delta A_{-BD}^*)$	Intra–domestic provinces
	$CE(A_{-BF}^*)$	Intra–foreign countries
	$CE(A_{DD}^*)$	Inter–domestic provinces
	$CE(\Delta A_{FF}^*)$	Inter–foreign countries
	$CE(\Delta A_{BD}^*)$	From Beijing to domestic provinces
	$CE(\Delta A_{BF}^*)$	From Beijing to foreign countries
	$CE(A_{DB}^*)$	From domestic provinces to Beijing
	$CE(\Delta A_{FB}^*)$	From foreign countries to Beijing
	$CE(A_{DF}^*)$	From domestic provinces to foreign countries
	$CE(\Delta A_{FD}^*)$	From foreign countries to domestic provinces
Final demand effect	$CE(\Delta P_B)$	Commodity structure
	$CE(\Delta S_B)$	Spatial structure
	$CE(\Delta K_B)$	Consumption scale

2.4   SPA of CBCE changes across "Local-Domestic-International" systems

SPA can identify changes in upstream sector carbon emissions driven by final consumption (Treloar, 1997; Mattila, 2013; Lin and Teng, 2022). Consequently, the SPA was used to explore the key paths of TCE_B change.

The SPA begins with a series expansion of the Leontief matrix, $L = (I-A)^{-1} = I+A+A^2+A^3+\cdots$. Applied to Equation (4), the total carbon flows can be expressed as the part directly and indirectly caused by Beijing's final demand:

$$TCE_B = c\left(I+A+A^2+A^3+\cdots\right)Y_B = cY_B+cAY_B+cA^2Y_B+cA^3Y_B+\cdots cA^nY_B \quad (10)$$

Of which, cY_B is the CO_2 emission of the first production layer (PL), describes Beijing's direct carbon emissions, expressed as follows: $Y_B \leftarrow$ Region 1 Sector 1. cAY_B is the CO_2 emission in the second PL, which denotes the carbon emissions triggered by PL1, expressed as follows: $Y_B \leftarrow$ Region 1 Sector 1 (R1 S1)$\leftarrow$ R2 S2. CA^2Y_B is the carbon emission in the third PL, which denotes the carbon emissions triggered by PL2, expressed as follows: $Y_B \leftarrow$ R1 S1$\leftarrow$ R2 S2$\leftarrow$ R3 S3. CA^nY_B is the carbon emission in PL $(n + 1)$, which denotes the carbon emissions triggered by PL(n), expressed as follows: $Y_B \leftarrow$ R1 S1$\leftarrow$ R2 S2$\leftarrow \cdots \leftarrow$ Rn Sn (Region 1, 2, $\cdots$,

n include Beijing, domestic provinces and foreign countries, Figure 4).

This study covers 74 regions, each containing 38 sectors and the A matrix is 3002-dimensional. To simplify the calculation, we combine 30 domestic provinces into D and 43 international countries into F; Beijing remains unchanged. We first find the key paths in D and F based on simplified data of 38 sectors in three regions; we then detail D and F to specific provinces and countries based on the key sectors in domestic and international key paths.
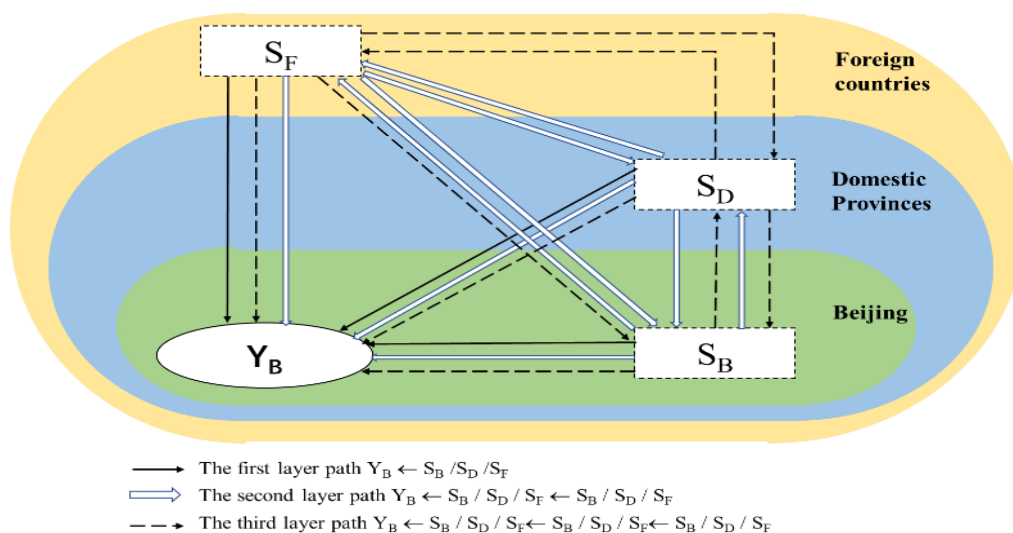

Figure 4: Key paths of Beijing's consumption-based carbon emission changes involving three systems

2.5   Data sources

CMRIO are found in several databases including CEADs, China National Information Centre, Minjun Shi and others. The most recent data available is the 2017 CMRIO published in CEADs database. IOT data are from the EXIOBASE database. We chose 2012 to compare the change in carbon emissions over five years, i.e. 2012–2017. According to CMRIO and IOT, data are available for Beijing, 30 domestic provinces (excluding Hong Kong, Macau and Taiwan) and 43 countries. The data on CO2 come from the corresponding satellite accounts of the two databases.

According to the Industrial Classification of National Economy, 42 sectors of CMRIO and 163 sectors of IOT were merged into 38 sectors (Appendix 3). Furthermore, region price deflators were adopted to adjust the CMRIO and IOT prices from 2012 to 2017 values. The price indices for China are available in the National Bureau of Statistics, and the GDP deflator for each country can be found on the World Bank website. IOT was converted to Chinese yuan (CNY) (million) denominated tables using annual average exchange rates provided by the State Administration of Foreign Exchange.

3. Main Results

3.1   Consumption-based carbon emissions of Beijing

According to the three-level nested EE-MRIO model, Beijing was empirically analysed using the method in 0. The results show that Beijing is a typical net carbon emission consumer. In 2012 and 2017, the ratio of consumption-based CO_2 to the production-side in Beijing was 2.71 and 2.06. Comparatively, Shanghai, a global financial centre, was 1.31 and 1.20 in 2012 and 2017, respectively (Shao et al., 2020). The ratio of Beijing was more than twice that of Shanghai, indicating that Beijing is a typical consumption-oriented city (Zhang et al., 2023); therefore, the city's CBCE should be given more attention. The consumption activities in Beijing cause local, domestic and international carbon emissions. First, the PCE induced by Beijing's consumption is the largest in the domestic system (PCE_{DB}), which was 80.65% and 80.29% in 2012 and 2017, respectively, followed by the local system and the smallest was the international system. Second, PCE_{BB} and PCE_{DB} decreased by 5.06% and 0.36%, meanwhile PCE_{FB} increased by 5.41% from 2012 to 2017 (Figure 5a).

In contrast, the ratio of value–added induced by Beijing's consumption to production is 1.03, far less than the carbon emission ratio. This result indicates significant room for reducing Beijing's consumption-based carbon emissions. Whether in 2012 or 2017, the PVA_{BB} is the largest, followed by PVA_{DB} and PVA_{FB} (Figure 5b). It shows that Beijing's economy is still predominantly involved in the domestic cycle, consistent with the findings of Zhang et al. (2022).
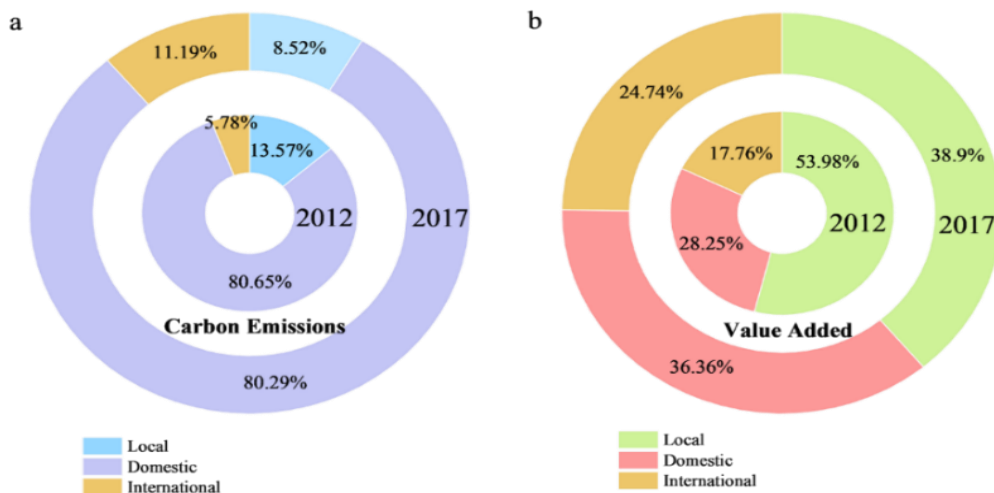

Figure 5: Distribution of carbon emissions (a) and value–added (b) in three systems

3.1.1   Carbon emissions changes in the local system

The local system has the largest share of value–added; however, it does not induce the highest share of carbon emissions. We can see that Beijing's local cycle yields high economic benefits and CO_2 emissions reduction.

Among the 38 sectors in Beijing, the participation of S28, S30 (Real estate), S24 (Construction) and S38 (Public administration) in the economic cycle deepens, while carbon emissions decline, as shown in quadrant IV of Figure 6. These sectors reduced carbon emissions and brought better economic gains. Of these, the most significant is S28, whose proportion of value-added (PVA) increased by 1.86% and the proportion of carbon emissions (PCE) decreased by 20.34%. S28 is a representative of the emerging service industry, which can create high value added with low resource and environmental consumption. The development of S28 is inseparable from Beijing's in-depth implementation of the innovation-driven development strategy and full promotion of the construction of the Science and Technology Innovation Centre. Beijing's basic research spending accounted for 14.7% of all social research and development spending in 2017, up nearly three percentage points from 2012. Regarding the change of S30 and S24, the possible reason is the shift of Beijing's real estate sector from an incremental development to a stock development phase. After the 2008 financial crisis, the real estate sector proliferated, creating a local small-cycle model of real estate-finance-local government infrastructure to drive economic growth; however, after 2016, real estate entered a phase of stock development. Demand for real estate has gradually declined; thus, the PCE induced by S24 and S30 declined in 2017.

In contrast, S11 (Processing of petroleum) and S26 (transport services) increased carbon emissions and reduced economic benefits, which indicates that these sectors are less technologically advanced and tend to emit more carbon. (Figure 6 quadrant II). S26 is a key energy consumption area, and S11 is a traditional high-energy sector, where large amounts of carbon dioxide accompany the extraction and processing of fossil energy. The changes in value-added and carbon emission ratios in most sectors (24 sectors in total) exhibit the same trend, which can be seen in quadrants I and III. The changes in other sectors are minimal, concentrating near the origin point (S3, S10, S12, S14, S15, S19, S21 and S37).
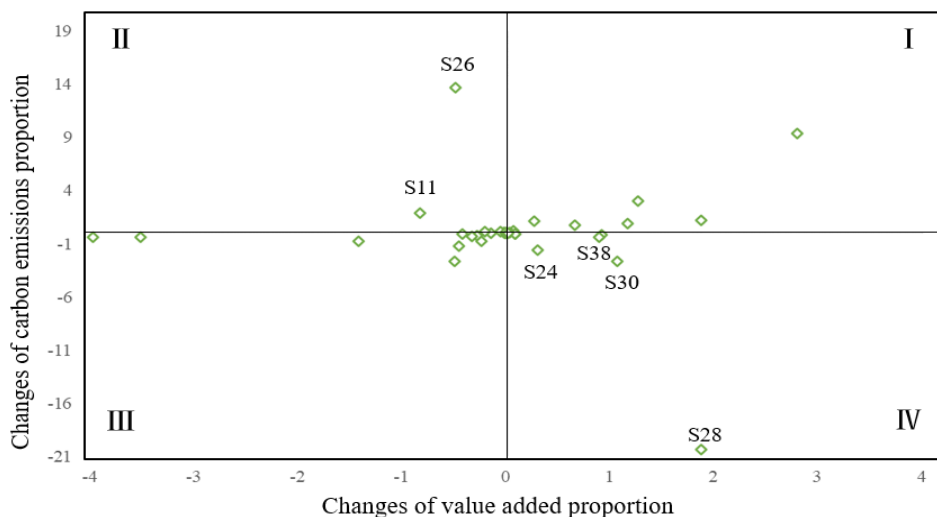

Figure 6: Changes in sectoral carbon emissions and value–added proportion in the local system

3.1.2 Carbon emissions changes in the domestic system

The domestic system has the largest share of carbon emissions, but the scale of carbon emissions has declined. The PVA_D increased by 8%, while the PCE_D decreased by 0.36%, suggesting that trading with Beijing for other provinces benefits domestic low–carbon development.

From a static view, Beijing has a tight carbon linkage with northern provinces. Regarding spatial layout, Beijing induced the most carbon emissions in provinces like Inner Mongolia, Hebei, Henan, Shanxi and Shandong, which are rich in natural resources and well-developed heavy industries. Regarding changes, the degree of carbon emission correlation between Beijing and these northern provinces decreased, except for Hebei, which increased slightly. We can look for reasons from a sectoral perspective. At the sectoral level, Beijing's high-tech and emerging sectors (S28, S32) induced an increase of PCE in the above five provinces. In contrast, carbon-intensive sectors (S24, S30 and S17) reduced the proportion of carbon emissions in these five provinces (Figure 7). Hebei is an important heavy industry base with high steel production. Shanxi, Inner Mongolia and Shandong have abundant coal resources and are close to Beijing; providing electricity to nearby Beijing can reduce transmission losses; thus, Beijing's carbon-intensive sectors (S24, S30 and S17) had more demand for these provinces and induced more carbon emissions in 2012. With the construction of 'four centres', Beijing has vigorously developed emerging industries. Beijing's emerging industries, which consume relatively few resources, have increased demand for Shanxi, Inner Mongolia and Shandong. Simultaneously, each province is making a strong effort to develop green and low-carbon technologies and is committed to providing clean electricity. In summary, Beijing has a strong carbon linkage with neighbouring northern provinces, and the carbon correlation between Beijing's emerging technology sector and these provinces is deepening. The carbon–intensive sector is the opposite.
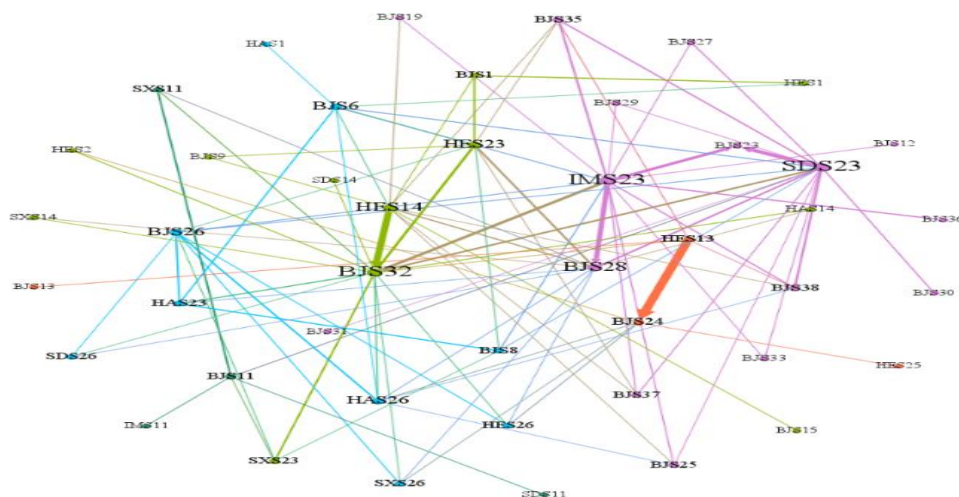

Figure 7: Changes in sectoral carbon emission ratios between Beijing and key provinces

Note: The thickness of the edge represents the magnitude of the proportional change.

Regarding economics, Beijing maintains close ties with southeast coastal regions. The proportion of value-added created by each province to TVA_D in 14 provinces has increased among 30 provinces. The top three are Guangdong, Jiangsu and Shanghai (Table 2), featuring prosperous economies and excellent technological innovation capabilities. Beijing deepens economic linkages with the three provinces mainly through S28, S32 and S19, which are part of the emerging service sectors and high–precision manufacturing.

Table 2: Changes in carbon emissions and value-added in the top five provinces induced by Beijing's consumption

Carbon emissions (Million tonnes)			
	2012	2017	Changes in proportion
IM	24.13 (12.34%)	13.68 (9.73%)	-2.61%
HE	21.70 (11.10%)	16.32 (11.61%)	0.51%
HA	14.93 (7.63%)	6.59 (4.69%)	-2.95%
SX	13.92 (7.12%)	7.59 (5.40%)	-1.72%
SD	13.05 (6.67%)	8.97 (6.38%)	-0.29%
Other provinces	107.84 (55.14%)	87.47 (62.20%)	
Value-added (billion)			
	2012	2017	Changes in proportion
GD	26.12 (0.93%)	95.43 (3.13%)	2.20%
JS	70.67 (2.51%)	122.81 (4.03%)	1.52%
SH	37.58 (1.33%)	70.01 (2.30%)	0.96%
ZJ	53.49 (1.90%)	86.04 (2.82%)	0.92%
HE	60.22 (2.14%)	80.00 (2.62%)	0.49%
Other provinces	2,570.90 (91.20%)	2,595.26 (85.10%)	

3.1.3 Carbon emissions changes in the international system

Trading with Beijing for foreign countries is beneficial to international low-carbon development. The PCE_F was the smallest in 2012 but increased in 2017. The PVA_F PCE_F and rose by 7% and 5.41%, respectively, indicating that foreign countries were providing products and services to Beijing at a lower cost in carbon emissions for a greater economic benefit.

Beijing's carbon linkages with some Western Europe Union (EU) countries are getting closer. Beijing induced the largest increase in the proportion of CO_2 emissions in some Western EU countries, such as Portugal, the Netherlands and Finland (Table 3), consistent with the findings of Jiang et al. (2023).

Table 3: Changes in carbon emissions and value–added in the top 5 countries induced by Beijing's consumption

Carbon emissions (Million tonnes)			
	2012	2017	Changes in proportion
Portugal	0.0001 (0.001%)	5.23 (26.69%)	26.69%
Netherlands	2.34 (16.67%)	4.08 (20.82%)	4.14%
Finland	0.42 (2.99%)	1.06 (5.38%)	2.39%
South Korea	0.0002 (0.001%)	0.0019 (0.01%)	0.01%
Denmark	0.0003 (0.001%)	0.0013 (0.01%)	0.01%
Other countries	11.26	9.23	
Value-added (Billion)			
	2012	2017	Changes in proportion
Germany	31.00 (6.11%)	61.41 (8.74%)	2.63%
Australia	5.82 (1.15%)	19.02 (2.71%)	1.56%
United States	70.72 (13.94%)	108.35 (15.42%)	1.48%
Japan	44.13 (8.70%)	67.78 (9.65%)	0.95%
South Korea	23.13 (4.56%)	35.95 (5.12%)	0.56%
Other countries	332.56	410.01	

The results show that the proportion of Portugal's carbon emissions induced by the demand for S17, S32 and S4 in Beijing has increased most (Figure 8). Beijing's S6, S17 and S15 increased the Netherlands' share of carbon emissions by 15.30%, 9.70% and 0.28%, placing them in the top three. Demand from the S32, S37 and S36 increased Finland's proportion of carbon emissions by 7.9%, 2.3% and 2.2%, with the rest of the sectors rising by less than 2%. Portugal is rich in metallic mineral resources and is an important copper producer. The main categories of goods imported by China from Portugal are electrical and spare parts (Ceatec, 2021). Most Dutch companies investing in China are production-oriented enterprises, such as Royal Dutch Shell and the Dutch International Group. Finland's three largest exports to China include electromechanical products, cellulose pulp and paper and base metals and products. Hence, the PCE of Portugal, the Netherlands and Finland has increased, induced by Beijing.

Beijing's economic linkages with highly developed economies like the United States (US), Germany and Japan have become closer. The PVA_F, the smallest among the three systems, has increased. This growth indicates that Beijing, as an international metropolis, actively connects with international circulation. Regarding the proportion of value–added by individual countries to the TVA_F, 17 of the 43 countries and regions have increased this share. The top 5 countries are Germany, Australia, the US, Japan and South Korea (Table 3). At the sectoral level, value–added in the above three countries is mainly induced by Beijing's highly sophisticated manufacturing and emerging services sectors (S17, S6 and S28).
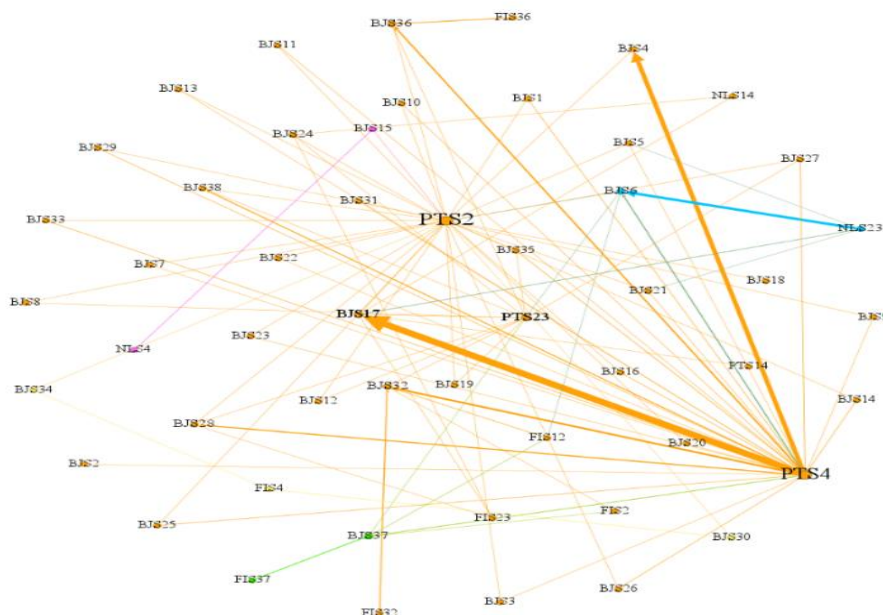
Figure 8: Changes in sectoral carbon emission ratios between Beijing and key countries

Note: The thickness of the edge represents the magnitude of the proportional change

3.2 SDA of CBCE reductions across "Local-Domestic-International" systems

Since 2012, Beijing has continued to optimise its consumption structure, forming a series of policies around the construction of the 'four centres'. During the study period, Beijing's consumption-based carbon emissions decreased by 67.36 Mt. We further use SDA to analyse the reasons for the changes in the above carbon emissions, determining that more than half of the factors contribute to the reduction of TCE_B.

The first type is the carbon emission intensity effect, which acts in different directions in different systems. In the local and domestic systems, the carbon intensity effect leads to a decrease, while in the international system leads to an increase (Figure 9). Since domestic production still meets most of Beijing's final demand, the decrease in CO_2 emission intensity in the domestic production sector is the main factor effectively suppressing TCE_B growth. Since 2012, China has been committed to co-regulating of pollution reduction and carbon reduction. China's 2020 carbon intensity 18.8% below 2015 (The Development and Reform Commission of China, 2020). Our results also indicate that China's measures have achieved good carbon reduction results. Internationally, with the evolution of development stages and the shift of high-carbon industries, major developed economies have all achieved carbon peaking (The Central People's Government of

the People's Republic of China, 2021). Nonetheless, the difficulty of reducing carbon intensity is increasing and marginal costs are increasing. For developing economies, industrialisation and urbanisation are still in progress and energy consumption will remain rigid; therefore, local and domestic carbon emissions are declining, while international emissions are rising slightly.
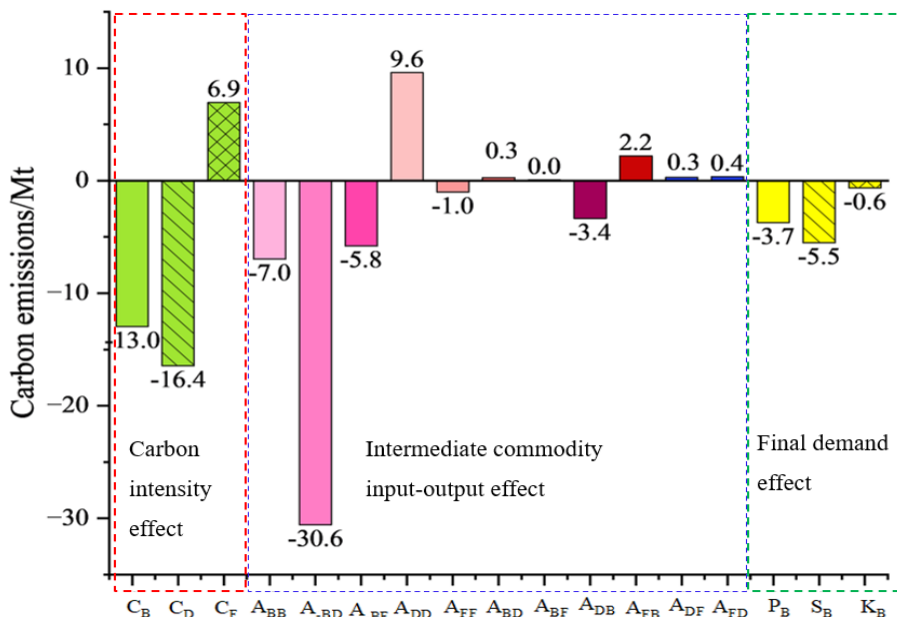

Figure 9: Driving factors for Beijing's consumption-based carbon emissions

The second type is the intermediate commodity input–output effect, which contains 11 factors. Out of the 11 factors, 6 carry substantial weight and can be further categorized into two distinct groups. The first category includes factors that promote the decrease in carbon emissions (negative factors), and the other category includes factors that increase carbon emissions (positive factors). In negative factors, $CE(\Delta A_{-BD}^{*})$ contributing 45.4% to carbon reduction. The contribution of $CE(\Delta A_{-BD}^{*})$ ranking first among 17 factors, which again shows that Beijing is mainly involved in the domestic cycle. The second is $CE(\Delta A_{BB}^{*})$ contributing 10.4% to TCE_B reduction. With technological progress and industrial restructuring, the input–output commodity structure in Beijing is gradually becoming low-carbon. The third is $CE(A_{-BF}^{*})$ which implies that the input–output commodity structure within countries also tends to be low–carbon. The fourth is $CE(A_{DB}^{*})$. The analysis in 3.1 shows that in the process of deepening the domestic cycle, Beijing's emerging service industries and high–precision manufacturing industries have increased their domestic demand. Therefore, the effect of domestic provinces' exports to Beijing reduces carbon emissions. In positive factors, $CE(A_{DD}^{*})$ leads to a 14.2% increase in TCE_B. In other words, domestic provinces contain significant carbon emissions

in intermediate products when trading with other provinces. Promoting various factors in the organic linkage of production, distribution, circulation and consumption is conducive to breaking the small local cycle and opening the large domestic cycle; however, the SDA results show that the inter-provincial flow of intermediate goods generates significant carbon emissions and is an important factor in increasing carbon emissions. Therefore, reducing carbon emissions from intermediate products is essential for smoothing the economic cycle and reducing carbon emissions. $CE(\Delta A_{FB}^{*})$ leads to a 3.2% increase in TCE_B potentially because Beijing's processing of imported intermediate products from abroad produces more carbon emissions.

The final demand effect contributes to a decrease in TCE_B. In particular, the change in the spatial structure effect resulted in a 5.5 Mt decrease in TCE_B, mainly because Beijing's main import partners are showing low-carbon development. The commodity structure effect also reduced TCE_B, with a contribution of 5.5%. Beijing is a service-oriented city with strong demand in the tertiary industry. Moreover, Beijing has vigorously promoted the construction of the 'four centres', with increasing domestic and international demand for emerging service sectors and high-precision manufacturing. These are low-carbon industries compared to wholesale and retail, accommodation, and catering sectors. Scale effect caused TCE_B to drop by 0.64 Mt; according to the nested MRIO, Beijing's final demand declined from 284.6 billion CNY in 2012 to 283.8 billion CNY in 2017, a decrease of 0.31%.

3.3 SPA of CBCE reductions across "Local-Domestic-International" systems

Section 3.2 showed that the intermediate commodity input-output effect significantly contributed to carbon emissions changes; however, due to SDA limitations, we were unable to conduct a detailed analysis. This study further used SPA to analyse sectoral correlations in order to obtain the key paths of TCE_B changes.

The distribution results of TCE_B at each PL can be obtained in 2012 and 2017, as shown in Table 4. Beijing's consumption-based carbon emissions are concentrated in the first seven PLs, accounting for more than 90%. Carbon emissions of PL1 occupied 11.1% and 8.7% in 2012 and 2017, respectively, comprising a relatively small share. The previous analysis shows that Beijing is a typical carbon emission consumer, which the SPA results confirm. The share of carbon emissions of PL2 triggered by the first production layer (PL1) reaches 22.1% and 20.2%. The PL3 accounted for 21.2% and 22.9%. The share of carbon emissions from the first three PLs in 2012 and 2017 is more than half the total. In terms of dynamic changes, the changes in carbon emissions of the first three production layers accounted for 61.34% of the total changes; therefore, this paper takes the first three production layers as the boundaries to identify the key paths of carbon emission changes of TCE_B. The top 10 industrial chain types contributing to Beijing's consumption-

based carbon emissions increase and decrease in 2012–2017 are selected for analysis.

Table 4: Distribution of TCE_B at different PLs in 2012 and 2017

Production layer	Year2012		Year2017		Carbon reduction	
	Carbon emissions	Cumulative percentage	Carbon emissions	Cumulative percentage	Carbon emissions	Cumulative percentage
PL1	26.99	11.13%	15.29	8.73%	11.70	17.37%
PL2	53.64	33.24%	35.46	28.97%	18.17	44.35%
PL3	51.53	54.48%	40.09	51.85%	11.44	61.34%
PL4	38.75	70.46%	30.84	69.45%	7.92	73.09%
PL5	26.26	81.28%	20.73	81.28%	5.53	81.30%
PL6	16.92	88.26%	13.07	88.74%	3.86	87.02%
PL7	10.66	92.66%	7.97	93.28%	2.69	91.02%

DS23 (electric power of domestic provinces) and DS24 (construction of domestic provinces) are key sectors in the top10 types of key paths for Beijing's consumption-based carbon emission increase (Figure 10). DS24 appeared six times, ranking first. With 51% of CO_2 emissions and 46% of energy consumption, the construction sector is the largest carbon emitter in China (Li et al., 2020). Construction causes large CO_2 emissions from the upstream industry sector (Hou et al., 2021). This paper's SPA results also indicate that domestic construction is a key node for the growth of Beijing's CBCE. DS23 appeared four times, ranking second. S23 consumes significant fossil fuels and is also a major carbon emitter. Analysis of key provinces through DS23 reveals that the S23 of Inner Mongolia has the greatest carbon increase; abundant coal resources have made Inner Mongolia an important comprehensive energy and power export base in China. Despite Inner Mongolia's commitment to transform its energy structure in recent years, coal still dominates its energy structure.
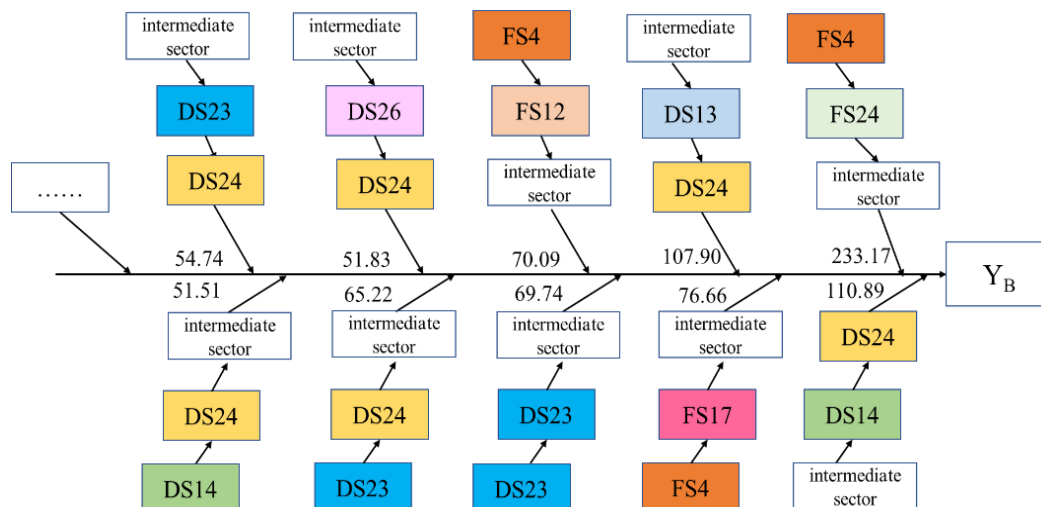
Figure 10: Top 10 types of key paths for Beijing's consumption-based carbon emission increase in 2012-2017

Note: The numbers by the arrows indicate the average increased carbon emissions on the whole path.

FS12 (chemical products of foreign countries), FS17 (transport equipment of foreign countries), FS6 (food and tobacco processing of foreign countries) and FS24 (construction of foreign countries) appear most frequently in the top 10 types of key paths for Beijing's consumption-based decrease in carbon emission; these are the key sectors for the reduction of TCE_B (Figure 11). FS12 appeared 11 times, ranking first. Analysis of key countries through FS12 reveals that Mexico's S12 has the most significant carbon reduction in the industry chains. Mexico is rich in petroleum and has a well-developed petrochemicals manufacturing industry. S12 of Mexico supplies S6, S36 and S24 in foreign countries with pesticides, food and feed additives, construction materials and medical drugs; carbon reductions from S12 to these sectors contribute to carbon reductions along the entire pathway. FS17, FS6 and FS24 appeared twice, ranking second. In contrast to DS24, FS24 plays a crucial role in the critical paths of CO_2 reduction, primarily due to the reduction in carbon emissions from the upstream sectors.
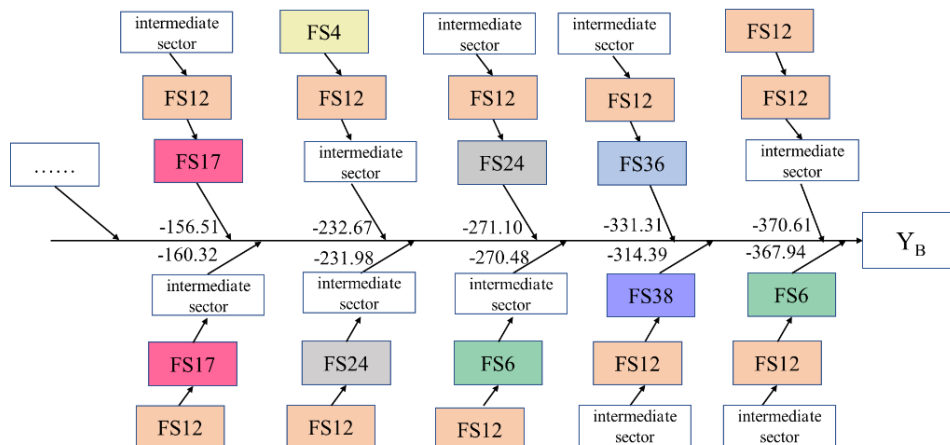
Figure 11: Top 10 types of key paths for Beijing's consumption-based carbon emission decrease in 2012-2017

Note: The numbers by the arrows indicate the average decreased carbon emissions on the whole path.

4. Conclusion

By constructing "Local-Domestic-International" nested EE-MRIO, this paper first measured the carbon emissions and value-added in local, domestic, and international systems from a consumption perspective. We then analysed the reasons for CBCE changes using SDA. Finally, SPA was adopted to identify the cross systems key pathways of CBCE changes. Here are the main conclusions.

The PCE induced by Beijing's consumption in the local, domestic, and international system is 8.52%, 80.29%, 11.19%, respectively. The proportion of value-added induced by Beijing's consumption in the local, domestic, and international system is 38.9%, 36.36%, 24.74%, respectively. From the perspective of carbon emissions and economic linkages, there is spatial inconsistency in carbon emissions and value-added induced by consumption in Beijing. Beijing has a tight carbon linkage with northern provinces at the domestic level, while Beijing maintains close ties with southeast coastal regions regarding economics. At the international level, Beijing's carbon linkages with some Western EU countries are getting closer. However, Beijing's economic linkages with some highly developed economies (Germany, Australia, the US, Japan and South Korea) have become closer. From the perspective of sector, Beijing's high-tech sector becomes strongly linked to carbon emissions in domestic northern provinces, carbon-intensive sectors increased the PCE in some Western EU countries.

SDA results indicate that the ICIOE of intra-domestic provinces, followed by domestic carbon intensity effect, are the most important driving force behind the decline of Beijing's CBCE. This is consistent with the conclusions of Dong and Zhang (2023). In addition, the decline of Beijing's carbon intensity and the ICIOE of intra-foreign countries are also the main factors contributing to the decline of Beijing's CBCE. This suggests a trend towards decarbonization of the intermediate

goods input structure within the provinces and foreign countries, and carbon intensity of the production sector in Beijing and domestic provinces is declining. On the contrary, the ICIOE of inter–domestic provinces are the most important factor leading to the increase of Beijing's CBCE. This demonstrates that there is a tendency for the intermediate product input structure to be highly carbonized among the domestic provinces. The comparison shows that the intermediate product input structure within provinces and countries is relatively low-carbon, while the greening of intermediate product inputs among provinces needs to be improved.

In the top 10 types of key paths for Beijing's CBCE growth, electric power and construction sectors in domestic systems. Construction industry is one of the largest end-use energy consumers and a major contributor to GHG emissions. This is because the construction sector drives the growth of carbon emissions in sectors such as the mining industries, the electric power industries, the transport industries, etc. At the same time, the power sector, with its high consumption of fossil fuels, is also key to the growth of carbon emissions. Chemical products, transport equipment, and food processing sectors in foreign systems are key sectors in the top 10 types of key paths for Beijing's CBCE decrease. This suggests that the sectors mentioned above in international system can drive metropolitan areas to achieve carbon reductions through the critical chain pathway.

Based on the above conclusions, we propose policy recommendations to help Beijing's CBCE reduction across "Local-Domestic-International" three systems.

Domestically, Beijing should further strengthen cooperation with emerging technology departments in provinces like Inner Mongolia, Hebei, Shanxi, Shandong, and Henan to promote economic development while achieving carbon reduction. Beijing can use its economic and technological advantages to develop low-carbon technologies and transfer them to regions such as Inner Mongolia and Hebei. At the international level, Beijing should strengthen cooperation with Western EU countries in emerging technology sectors. Beijing can simultaneously try to promote cooperation among governments of various countries, jointly formulate carbon tariff standards and coordinate policies.

Based on the conclusion that the ICIOE of intra-domestic provinces, and domestic carbon intensity effect are the most important driving force behind the decline of Beijing's CBCE, consideration could be given within provinces to further optimising the structure of intermediate product inputs, and reduce carbon emissions in the process of handling intermediate product processing. Based on the conclusion that the ICIOE of inter-domestic provinces are the most important factor leading to the increase of Beijing's CBCE, low–carbon cooperation of intermediate products among provinces is a direction worth paying attention to in the future. Upstream provinces should provide low–carbon and clean intermediate products for downstream provinces, while downstream provinces should also enhance their technological capabilities during the intermediate product processing stage. Furthermore, Beijing should optimise its trade structure and import products from those countries with lower carbon emission intensity.

The following policies can be considered to reduce carbon emissions in

metropolises of developing countries, such as Beijing. First, the domestic electric power sector should gradually replace coal with clean energy and plan ahead for new energy consumption. The construction sector in domestic and international system should strengthen energy use efficiency, adopt energy-saving technologies, and develop green buildings. Secondly, Beijing can strengthen exchanges and co-operation with international chemical, transport equipment, and food processing sectors. Third, consideration could be given to optimizing the trade structure and strengthening technical cooperation among "Local-Domestic-International" systems to develop low-carbon technologies.

The research in this paper is instructive for developing country capitals to achieve carbon emission reduction on the consumption side, further exploiting the potential for carbon emission reductions in developing country capitals, contributing to the mitigation of global climate change. Due to data availability constraints, latest data available as of 2017. As new input-output tables become available, the data may be updated in subsequent studies.

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Appendix
Appendix 1: Eleven factors after A decomposition

Factors	Processing	Implications
A^*_{bb}	*All elements of A except the submatrix A_{bb} is replaced by 0*	Intermediate product use structure in Beijing
A^*_{-bD}	*All elements of A except the submatrix A_{ii} (i=D1, D2, ···D30) is replaced by 0*	Intermediate product use structure within provinces
A^*_{-bF}	*All elements of A except the submatrix A_{ii} (i=F1, F2, ···F43) is replaced by 0*	Intermediate product use structure within countries
A^*_{Db}	*All elements of A except the submatrix A_{Db} is replaced by 0*	Beijing's backward industry linkages with domestic
A^*_{Fb}	*All elements of A except the submatrix A_{Fb} is replaced by 0*	Beijing's backward industry linkages with international
A^*_{bD}	*All elements of A except the submatrix A_{bD} is replaced by 0*	Beijing's forward industry linkages with domestic
A^*_{bF}	*All elements of A except the submatrix A_{bF} is replaced by 0*	Beijing's forward industry linkages with international
A^*_{DD}	*All elements of A except the submatrix A_{DD} is replaced by 0*	Industry linkages between provinces
A^*_{FF}	*All elements of A except the submatrix A_{FF} is replaced by 0*	Industry linkages between countries
A^*_{DF}	*All elements of A except the submatrix A_{FF} is replaced by 0*	Domestic's forward industry linkages with international
A^*_{FD}	*All elements of A except the submatrix A_{FD} is replaced by 0*	Domestic's backward industry linkages with international

Appendix 2: Provinces, countries and territories in the three-level nested input-output table

System	Including provinces, countries and regions
Local	Beijing (BJ)
Domestic	Tianjin(TJ), Hebei(HE), Shanxi(SX), InnerMongolia(IM), Liaoning(LN), Jilin(JL), Heilongjiang(HL), Shanghai(SH) Jiangsu(JS), Zhejiang(ZJ), Anhui(AH), Fujian(FJ), Jiangxi(JX), Shandong(SD), Henan(HA), Hubei(HB), Hunan(HN), Guangdong(GD), Guangxi(GX), Hainan(HI), Chongqing(CQ), Sichuan(SC), Guizhou(GZ), Yunnan(YN), Xizang(XZ), Shaanxi(SN), Gansu(GS), Qinghai(QH), Ningxia(NX), Xinjiang(XJ)
International	Austria,Belgium, Bulgaria、 Cyprus, CzechRepublic, Germany, Denmark, Estionia, Spain, Finland, France, Greece, Croatia, Hungary, Ireland, Italy, Lithuania, Luxembourg, Latvia, Malta, Netherlands, Poland, Portugal, Romania, Sweden, Slovenia, Slovak Republic, Great Britain, United States, Japan, Canada, Korea, Brazil, India, Mexico, Russia, Australia, Switzerland, Turkey, Norway, Indonesia, Zuid-Afrika, Other regions of the world.

Appendix 3: The sector names and codes

Code	Merged Sectors	Sectors in CMRIO
S1	Agriculture, Forestry, Animal Husbandry and Fishery	Agriculture, Forestry, Animal Husbandry and Fishery
S2	Mining and washing of coal	Mining and washing of coal
S3	Extraction of petroleum and natural gas	Extraction of petroleum and natural gas
S4	Mining and processing of metal ores	Mining and processing of metal ores
S5	Mining and processing of nonmetal and other ores	Mining and processing of nonmetal and other ores
S6	Food and tobacco processing	Food and tobacco processing
S7	Textile industry	Textile industry
S8	Manufacture of leather, fur, feather and related products	Manufacture of leather, fur, feather and related products
S9	Processing of timber and furniture	Processing of timber and furniture
S10	Manufacture of paper, printing and articles for culture, education and sport activity	Manufacture of paper, printing and articles for culture, education and sport activity
S11	Processing of petroleum, coking, processing of nuclear fuel	Processing of petroleum, coking, processing of nuclear fuel
S12	Manufacture of chemical products	Manufacture of chemical products
S13	Manufacture of non-metallic mineral products	Manuf. of non -metallic mineral products
S14	Smelting and processing of metals	Smelting and processing of metals
S15	Manufacture of metal products	Manufacture of metal products
S16	Manufacture of general and special purpose machinery	Manufacture of general purpose machinery; Manufacture of special purpose machinery
S17	Manufacture of transport equipment	Manufacture of transport equipment
S18	Manufacture of electrical machinery and equipment	Manufacture of electrical machinery and equipment
S19	Manufacture of communication equipment, computers and other electronic equipment	Manufacture of communication equipment, computers and other electronic equipment
S20	Manufacture of measuring instruments	Manufacture of measuring instruments
S21	Other manufacturing and waste resources	Other manufacturing and waste resources
S22	Repair of metal products, machinery and equipment	Repair of metal products, machinery and equipment
S23	Production and distribution of electric power, heat power, gas and tap water	Production and distribution of electric power and heat power; Production and distribution of gas; Production and distribution of tap water
S24	Construction	Construction
S25	Wholesale and retail trades	Wholesale and retail trades
S26	Transport, storage, and postal services	Transport, storage, and postal services
S27	Accommodation and catering	Accommodation and catering
S28	Information transfer, software and information technology services	Information transfer, software and information technology services
S29	Finance	Finance
S30	Real estate	Real estate
S31	Leasing and commercial services	Leasing and commercial services
S32	Scientific research and Polytechnic services	Scientific research; Polytechnic services

S33	Administration of water, environment, and public facilities	Administration of water, environment, and public facilities
S34	Resident, repair and other services	Resident, repair and other services
S35	Education	Education
S36	Health care and social work	Health care and social work
S37	Culture, sports, and entertainment	Culture, sports, and entertainment
S38	Public administration, social insurance, and social organizations	Public administration, social insurance, and social organizations