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# Unveiling key drivers of urban embodied and controlled carbon footprints

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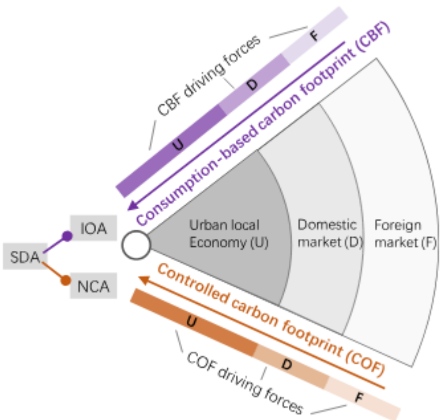
## HIGHLIGHTS

- Controlled footprint traces the actual carbon emissions controlled by cities.
- Only 60% of the total carbon footprint is controlled by urban consumption.
- Control perspective reveals production structure highly impacts carbon footprint.

## GRAPHICAL ABSTRACT

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## ABSTRACT

Fast-growing urban demand drives increase of production at a global scale. A full understanding of how carbon footprint is driven by socioeconomic factors in local, domestic and international economies is essential. Herein, we develop a cross-boundary carbon tracking approach based on input-output analysis, network control analysis and structural decomposition analysis. Using Beijing as a case study, we quantify both urban embodied and controlled carbon footprints over 1985–2012, and look into how they are impacted by socio-economic factors in local, domestic and foreign regions. We find that the carbon controlled by urban economy from inside accounts for 60% of the total footprint over 1985–2000, while this proportion decreased to 45% in 2012 due to externalization of production supply chains. Carbon intensity and urban consumption strongly compete with each other and together determine the variation trend of the city's consumption-based and controlled carbon footprint. Compared to a consumption-based perspective, this control approach reveals a higher impact of production structure transition on urban carbon footprint, and clearly tracks how carbon emissions are increasingly manipulated by other regions. The local-production-related carbon footprint have decreased by 15–22% over 2000–2012, while meanwhile that from domestic and foreign imports has increased dramatically by 700–960%. Network control approach is able to unveil drivers of carbon emission that are actually regulated by a city as a consequence of its interactions with the rest of global economy.

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## 1. Introduction

It is expected that the world will double its urban population from 3.3 billion in 2017 to 6.4 billion by 2050 [1]. While developed countries will remain at a high level of urbanization, developing nations in Asia, South American and Africa will experience a high-speed urban expansion in the coming decades [2]. Cities have a fairly close linkage with global warming because a major part of greenhouse gas emissions are released from or induced by human activities in urban areas [3,4]. The construction of low-carbon city is also at the core of promoting urban sustainability [5,6].

Inventory approaches and metrics are critical in delineating urban carbon footprints. Input-output analysis (IOA) has been widely used in addressing various environmental problems such as land use [7,8], water use [9,10], materials use [11], biodiversity loss [12], energy consumption [13,14] and $CO_2$ emissions [15–17]. For cities, almost all products are made of resources extracted from rural areas or ecosystems outside urban boundaries, making cities as consumers in global economy [18,19]. The import of goods to boost urban economic growth results in "upstream carbon emissions" from domestic and foreign markets [20,21]. This arouses a major challenge for local authorities to efficiently manage urban carbon flows [22]. Compared to territorial carbon inventory approach, IOA is capable of evaluating the carbon footprint of an economy from a consumption perspective [23], and tracking the transfer of carbon emissions across administrative boundaries through trade [24]. One can look into how regions contribute differently to a city's carbon footprint in order to meet its demand [25]. For example, a three-scale IOA [20,26] was proposed to assess the carbon footprint of Beijing by differentiating the technologies of production activities of different regions the city relies on. In order to determine the drivers of changing carbon footprints, structural decomposition analysis (SDA) is often used to decompose socioeconomic factors captured by input-output model [27–29]. This approach provides significant insights into why the carbon footprint of a region changes over time and what factors should be targeted for future decarbonization [30–32].

On the other hand, how carbon emissions can be regulated based on inter-sector relationships in carbon flow networks has attracted increasing attention e.g. [33,34]. Network Control Analysis (NCA) [35], a metrics derived from Ecological Network Analysis, has been widely used to evaluate the relationship among components in both natural and urban systems e.g. [36,37]. NCA has been used to analyze inter- sectors control associated with material and energy flows in urban economy [38] or industrial parks [39]. The concept of controlled emission has been proposed to determine how much carbon emission is actually controlled by a sector or a region based on pair-wise carbon flow between them, which uncovers the control mechanism of emissions [40]. However, the controlled carbon footprint has not been tracked on a cross-boundary basis for cities. The driving forces of urban controlled carbon footprint along the whole urban supply chains are unclear. A finer decomposition of carbon footprint by sources of production along the supply chains is also needed to provide a comprehensive perspective of what drivers the dynamics of controlled carbon footprint. These supplements will significantly enhance our understanding of how much potential of decarbonization can be released within the urban economy still and how much is resting upon optimizing upstream supply chains.

In this study, we analyze the dynamics of urban carbon flows of Beijing originated from local, domestic and foreign economies from 1985 to 2012. A system-based tracking approach of carbon flows at sector level is developed by integrating IOA, NCA and SDA. The quantification of urban carbon footprint takes the difference in production efficiencies and economic structures in different regions into account by linking China's multi-region input–output table (MRIO) to the global economy. On this basis, we evaluate how consumption-based carbon footprint (CBF) and controlled carbon footprint (COF) are driven by various socioeconomic factors. By doing so, we aim to: (1) track the carbon flows triggered by urban final demand on a cross-boundary basis and derive in-depth insight into what drive the change in urban carbon footprints; (2) manifest what controlled carbon footprint can supplement and enhance our current understanding of urban carbon flows; (3) determine what role the urban economy within city boundary and inter-linking economy in other regions should play in decarbonization. The rest of the paper is arranged as follows: Section 2 introduces the development of integrated approach and how it is applied to the case study. Section 3 illustrates the results of carbon accounting and discuss the underpinning policy implication. A set of conclusions are given in the final section (Section 4).

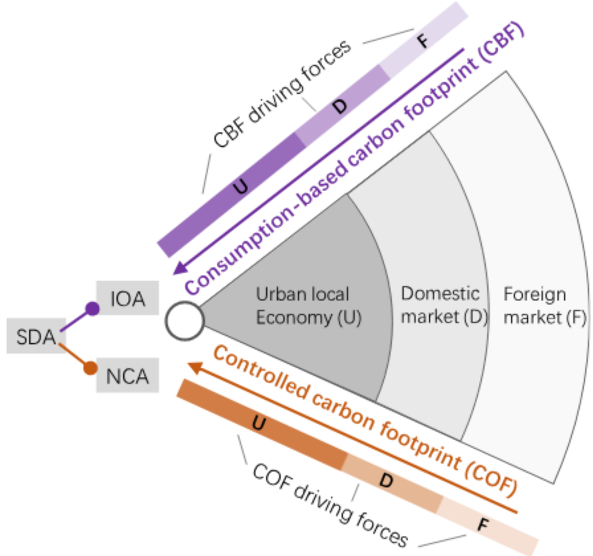


**Fig. 1.** A system-based tracking approach for cross-boundary urban carbon footprint. SDA: structural decomposition analysis; NCA: network control analysis; IOA: input-output analysis.

## 2. Materials and methods

### 2.1. Framework for tracking cross-boundary urban carbon flows

A conceptual framework of tracking cross-boundary urban carbon flows is presented in Fig. 1. The commonly-defined territorial emissions (Scope 1) as well as the emissions caused by upstream production for electricity supply (Scope 2) and other products (Scope 3) [41] consumed by a city are calculated in this study. On this basis, the consumption-based carbon footprint (CBF) and controlled carbon footprint (COF) of a city are calculated with decomposition into three parts: urban in-boundary (U) carbon emissions (or territorial emission), upstream emissions from domestic (D) and foreign (F) imports. The socioeconomic factors (i.e. emission intensity, economic production structure, consumption structure, per capita consumption volume and population) that drives the variation of carbon footprint over time are assessed for both CBF and COF, with further decomposition into the contribution of different final demand categories. This is achieved by fusing IOA, NCA and SDA based on a consistent system boundary of carbon flows.

### 2.2. Direct carbon inventory

Calculating direct carbon emissions is the basis of the accounting of CBF and COF. The carbon inventory approach of energy and industrial processes is based on the guideline from Intergovernmental Panel on Climate Change [42]. The main types of primary energy consumption used in Beijing are included [i.e. coal (including raw coal, other coal washing and briquette coal), coke, coke oven gas (including other coal gas), petrol, kerosene, diesel, liquefied petroleum gas (LPG) and natural gas]. Electricity and thermal power, as secondary energy types, are not included in the direct carbon inventory. The carbon emissions from industrial process mainly consider the production of cement (including clinker) and steel. Direct carbon emission (DCE) from energy consumption of a city is calculated by multiplying the consumption amount of a certain type of fuel or industrial process ($k$) by a sector ($i$) with the respective $CO_2$ emission coefficient (Eq. (1)).

$$\mathrm{DCE} = \sum_{i=1} \sum_{k=1} \mathrm{activity}(i,\, k) \times \mathrm{Emission\ coefficient}(i,\, k) \tag{1}$$

### 2.3. Consumption-based carbon footprint accounting

Input-Output Analysis (IOA) has been widely used to quantify carbon emission embodied in supply chains of products and services [43]. Multi-region input–output model (MRIO) is considered as an advance approach in cross-boundary urban carbon footprinting in that it differentiates production efficiencies and economic structures of various regions the city relates to [44,45]. Here a cross-boundary IOA has been established by linking the China MRIO table and the global economy, whereby the economic flows between the city and other regions are established. The compilation of intermediate flows and final demands is achieved below:

$$(x^{0u})_{n\times n} = \hat{t} \times (x^{0d})_{n\times n} \tag{2}$$

$$(y^{0u})_{n\times 1} = \hat{t} \times (y^{0d})_{n\times 1} \tag{3}$$

where intermediate flow and final demand between the city and other regions $x^{0u}$ and $y^{0u}$ are calculated from intermediate flow and final demand between China and other regions $x^{0d}$ and $y^{0d}$ from the global MRIO table. $t = Z^{0u}/\sum Z^{0u}$, $Z^{0u}$ is the import to a city/region derived from China MRIO table, $\hat{t}$ is the diagonal matrix of $t$.

On this basis, CBF is decomposed into three parts: (1) carbon emission released from activities within urban territorial, (2) carbon emission caused by production in the domestic market outside the city to satisfy urban consumption, and (3) carbon emission caused by production in the foreign market outside the city to satisfy urban consumption. The city's CBF from different sources are calculated by the following equations:

$$CBF^u = \theta_{1\times rn} L_{rn\times rn} y^u_{rn\times 1} \tag{4}$$

$$CBF^d = \theta_{1\times rn} L_{rn\times rn} y^d_{rn\times 1} \tag{5}$$

$$CBF^f = \theta_{1\times rn} L_{rn\times rn} y^f_{rn\times 1} \tag{6}$$

$$CBF^{total} = \theta_{1\times rn} L_{rn\times rn} y_{rn\times 1} = CBF^u + CBF^d + CBF^f \tag{7}$$

$$\boldsymbol{y}^u_{rn\times 1} = \begin{pmatrix} y^u_1 \\ y^u_2 \\ \cdots \\ y^u_n \\ 0 \\ \cdots \\ 0 \\ \cdots \end{pmatrix}_{rn\times 1} \quad \boldsymbol{y}^d_{rn\times 1} = \begin{pmatrix} \cdots \\ 0 \\ y^d_1 \\ y^d_2 \\ \cdots \\ y^d_n \\ 0 \\ \cdots \end{pmatrix}_{rn\times 1} \quad \boldsymbol{y}^f_{rn\times 1} = \begin{pmatrix} \cdots \\ 0 \\ \cdots \\ 0 \\ y^f_1 \\ y^f_2 \\ \cdots \\ y^f_n \end{pmatrix}_{rn\times 1} \tag{8}$$

where $L_{rn\times rn} = (I - A_{rn\times rn})^{-1}$, $A = [a_{ij}]$, $a_{ij} = x_{ij}/X_i$, $x_{ij}$ is the monetary flows from sectors $i$ to $j$ in the city-global MRIO table; $X_i$ is the total output of sector $i$; I is the identity matrix, $r$ is the number of regions and $n$ is the number of sectors in each region. $L_{rn\times rn}$ represents the total technical coefficient matrix connecting local, domestic and foreign economy. $\theta_i^{(t)}$ is the carbon emission intensities of economic sectors in all regions. $\boldsymbol{y}^u_{rn\times 1}$, $\boldsymbol{y}^d_{rn\times 1}$ and $\boldsymbol{y}^f_{rn\times 1}$ represent the final consumption of the city provided by local, domestic and foreign (including urban consumption, rural consumption and fixed capital formation). $CBF^u$, $CBF^d$ and $CBF^f$ represent the consumption-based carbon footprint originated from local, domestic and foreign production, respectively.

### 2.4. Controlled carbon footprint accounting

Network Control Analysis has been developed to identify the role of domination among different system components [35,36]. The metrics of control analysis is found useful in quantifying the dominance among various sectors or regions in energy and carbon flow networks [40]. The controlled carbon emission is the amount of emission that are controlled by a sector or a region based on the supply chains. For example, electricity sector can have control over manufacturing, thus contributing the carbon footprint of the latter. One the hand, electricity sector can be controlled by upstream mining sector and produce the footprint via this control relation. Compared to CBF, the controlled carbon footprint (COF) refers to the carbon emissions which are directly or indirectly controlled by the region due to the supply chain. We use COF to determine the carbon emission controlled by a city originated from different regions (local, domestic and foreign). The calculation process is as follows:

$$N_{rn\times rn} = L - L' = (I - A)^{-1} - (I - A')^{-1} \tag{9}$$

$$COF^u = \theta_{1\times rn} N_{rn\times rn} y^u_{rn\times 1} \tag{10}$$

$$COF^d = \theta_{1\times rn} N_{rn\times rn} y^d_{rn\times 1} \tag{11}$$

$$COF^f = \theta_{1\times rn} N_{rn\times rn} y^f_{rn\times 1} \tag{12}$$

$$COF^{total} = =COF^u + COF^d + COF^f = \theta_{1\times rn} N_{rn\times rn} (y^u_{rn\times 1} + y^d_{rn\times 1} + y^f_{rn\times 1}) \tag{13}$$

where $N_{rn\times rn}$ is a non-dimensional matrix derived from two technical coefficient matrices of opposite directions. It denotes the dominance of sector $j$ over sector $i$, which is used to quantify the controlled carbon emission of the former sector. $A' = [a'_{ji}]$ and $a'_{ji} = x_{ji}/x_i$. $COF^u$, $COF^d$ and $COF^f$ represent the controlled carbon footprint originated from local, domestic and foreign production, respectively.

### 2.5. Quantification of driving forces of carbon footprints

Structural decomposition analysis (SDA), with a close link to input-output model, has been applied to determine the contribution of socio-economic factors to environmental footprints over time [46,47]. The core idea of SDA is taking one factor in the economic system as a target variable, and the changes of the target variable are decomposed into several independent variables to measure their contribution to the target variable [27,28]. CBF and COF can be decomposed into the following forms:

$$\begin{aligned} CBF = CBF^u + CBF^d + CBF^f &= \theta_1 L_1 y_{\_s1} y_{\_v1} p_1 + \theta_2 L_2 y_{\_s2} y_{\_v2} p_2 \\ &\quad + \theta_3 L_3 y_{\_s3} y_{\_v3} p_3 \end{aligned} \tag{14}$$

$$\begin{aligned} COF = COF^u + COF^d + COF^f &= \theta_1 N_1 y_{\_s1} y_{\_v1} p_1 + \theta_2 N_2 y_{\_s2} y_{\_v2} p_2 \\ &\quad + \theta_3 N_3 y_{\_s3} y_{\_v3} p_3 \end{aligned} \tag{15}$$

where $\theta_i$, $y_{\_si}$, $y_{\_vi}$, $p_i$ are carbon emission intensity, consumption structure, per capita consumption volume and population, respectively, in respective to urban, domestic and foreign economies. $L_i$ and $N_i$ represent economic production structure and control structure, respectively. The contributions of these five socioeconomic factors to the variation in CBF and COF are captured in Eqs. (16)–(17). These contributions of factors can be further decomposed by dividing final consumption into urban consumption, rural consumption and capital formation.

$$\begin{aligned} \Delta CBF &= \Delta\theta L y_{\_s} y_{\_v} p + \theta \Delta L y_{\_s} y_{\_v} p + \theta L \Delta y_{\_s} y_{\_v} p + \theta L y_{\_s} \Delta y_{\_v} p \\ &\quad + \theta L y_{\_s} y_{\_v} \Delta p \end{aligned} \tag{16}$$

$$\begin{aligned} \Delta COF &= \Delta\theta N y_{\_s} y_{\_v} p + \theta \Delta N y_{\_s} y_{\_v} p + \theta N \Delta y_{\_s} y_{\_v} p + \theta N y_{\_s} \Delta y_{\_v} p \\ &\quad + \theta N y_{\_s} y_{\_v} \Delta p \end{aligned} \tag{17}$$

### 2.6. Case study and data sources

We take Beijing as a case study to assess its urban carbon footprint over 1985–2012 for two reasons: First, as the capital of China, the urbanization process in Beijing is very rapid over the research period. The population in 1985 was 9.81 million, while in 2012 it increased to 20.69 million. What is more important is that the personal consumption increased at an even higher rate, which can be seen from the increment of per capita GDP by around 20 times. Beijing provides a typical urbanizing sample where both increase in population and per capita consumption is contributing to the change in carbon emissions. Second, there are credible data of energy use and industrial process published each year, and single-region and multi-region input-output tables of Beijing (provincial-level city) can be used in the indirect carbon flows accounting. This will serve as a demonstration of how a city can restrain its carbon impact from a consumption perspective.

The direct energy consumption of each sector, economic and population data involved in this research are derived from the Beijing Statistical Yearbook. The carbon emission coefficient for primary energy types can be obtained from Compilation guide for provincial GHG inventory of Chin and the Intergovernmental Panel on Climate Change. The input-output table in 1985, 2000 and 2012 are from the Beijing Statistical Bureau. The China MRIO tables are connected to the global MRIO tables in a consistent way. China's MRIO table [48,49] consists of economic flows among 30 provinces (or provincial cities) and each province has 30 sectors (the most commonly-used version). The Global MRIO table from World Input-Output Database [50] depicts economic relationships between China and other regions in the world in a 35-sector format. All these tables are compiled by a 24-sector format and adjusted to constant prices in 2000. Since there no direct source of international trade data at provincial level, we assume Beijing imports from and exports to foreign regions in a similar structure with the nation. We make the best match of MRIO tables with the concerned years (1985, 2000 and 2012), otherwise we use the technical coefficient matrices of the closest year to approximate the situation. RAS technique [51] is used to re-balance the city-oriented MRIO tables.

## 3. Results and discussion

### 3.1. Variation in urban CBF and COF over time

Fig. 2 shows the variation of consumption-based carbon footprint (CBF) and controlled carbon footprint (COF) of urban sector. The rapid urbanization of Beijing has led to a major increase in both CBF and COF over the last three decades. The total COF only accounts for 60% of the CBF in 1985 and 2000, and 45% in 2012. This clearly shows that some of the increased carbon flows induced by urban consumption may not be controlled by the city fully; instead, other regions along the supply chain outside the city could be dominating these increased carbon flows.

Between 1985 and 2012 CBF grew by 480% (193 Mt), while COF increased by 340% (84 Mt) within the same period. The urban carbon footprint grew by about 6.7% each year on average from a consumption-perspective, which is slight faster than the increase in its controlled footprint (5.7% each year). The CBF and COF of the city share a similar speed of change over 1985–2000 (about 6.5%). But after 2000 the growth rate of COF slows down to 4.5%, while the CBF keep increasing in the same pace as before. The sector contribution to CBF and COF of Beijing has also undergone a notable change over time (the aggregation of sector is provided in Table A1). The proportion of carbon footprint in manufacturing sector has shrunk from 63% in 1985 to 21% in 2012 for CBF, and similarly from 65% to 32% in terms of COF. The proportion of services sector and agriculture sector remain stable. In comparison, the contribution of supply of electricity, gas and hot water has been grown fast. It accounts for about 21% and 26% in 1985 for CBF and COF, respectively. In 2012, as the demand for energy increased, the supply of electricity, gas and hot water accounts for the largest proportion (50% for CBF and 41% for COF, respectively). Another notable change is transportation, whose proportion has increased by about 2 times from 1985 to 2012 concerning both CBF and COF.

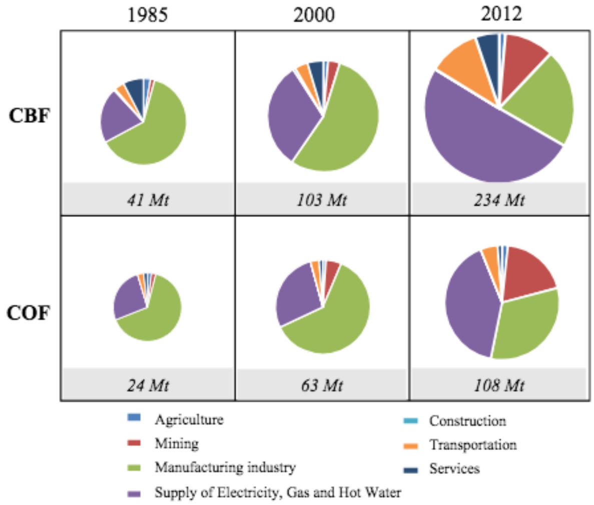


**Fig. 2.** Sector contribution to the variation of CBF and COF of Beijing over 1985–2012.

### 3.2. Urban CBF and COF from local, domestic and foreign production

Fig. 3 shows the consumption-based carbon footprint (CBF) and controlled carbon footprint (COF) of Beijing originated from local, domestic and foreign production in 1985, 2000 and 2012. The contribution of all three categories of final demand excluding export (i.e. urban consumption, rural consumption and fixed capital formation) to CBF and COF is also presented.

The evolution of CBF and COF is reflected by the contributions of different sources of production to total urban carbon footprints. Despite the total CBF and COF keep increasing over 1985–2012, the carbon emissions caused by local production within urban territory first-ascended but then descended. The local-production-related CBF decreased by 15%, while local-production-related COF also experience a 22% decrement between 2000 and 2012. In contrast, the CBF and COF originated from domestic and foreign area has been increasing dramatically by 700% and 960% in the meantime. Therefore, the increase of total CBF and COF during this period is mainly caused by the purchase from domestic and foreign markets. In 2012, the ratio among local, domestic and foreign production in CBF is 6:10:3, while the ratio among local, domestic and foreign resources in COF is 9:10:4. A major part of the $CO_2$ emissions triggered by Beijing's consumption are originated from other regions in China and the international imports also become an important source of carbon footprints. Like most large cities, Beijing has an increasingly high reliance on other regions outside urban territory (hinterlands) and thus externalized a large amount of carbon emissions via the outsourcing of supply chains.

For local-production-related CBF, the fixed capital formation is the largest part in all final consumption categories, accounting for 62% in 1985 and then decreasing to 50% in 2012. The role capital formation is even bigger from a controlled perspective in that it drives 72% of the total COF in 1985, then it decreases to 66% in 2012. Meanwhile, the proportions of fixed capital formation in domestic and foreign production footprints are reduced too, from about 50% to 30% over this period, for both CBF and COF. The significant role of capital formation in total carbon consumption-based footprint was also found in previous work [20,52]. In comparison to these one-year results, we find that over a long period of urbanization (1985–2012), capital formation still accounts for a very important part of Beijing's carbon footprint, not only

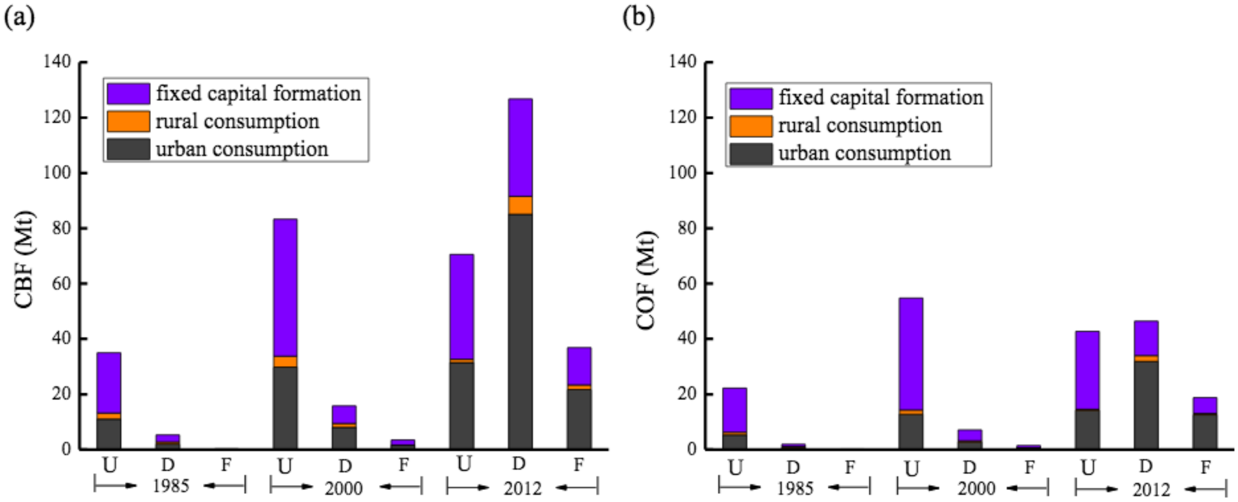


**Fig. 3.** The changing (a) CBF and (b) COF induced by local, domestic and foreign production.

in terms of local production but also increasingly from external markets. Beijing is still at the stage of large-scale construction in its demolition-reconstruction activities and urban sprawl, which will require a lot of carbon-intensive products, resulting in a large amount of carbon footprint, especially from the city and its suburb districts.

The carbon footprints related to urban residential consumption are increasingly produced by domestic and foreign markets, whose contributions are 60–67% in 2012 for CBF, compared to 28–38% in 1985. COF has a similar trend of change except that the ratio of domestic and foreign fraction become more important. On the other hand, many domestic and foreign imported products pour into urban households and cause huge increase in carbon footprints of the city. It has been reported that a large proportion of carbon footprint of Beijing is originated from domestic and foreign regions, mainly because of the growing urban residential consumption [23,45]. We find that local, domestic and international economies play different roles in carbon footprints triggered by various categories of final demands. From a consumption-based or controlled perspective, it is equally important to watch the attraction of carbon footprints induced by both fixed capital formation and urban households.

### 3.3. Socioeconomic drivers of changes in CBF and COF

Fig. 4 shows the contributions of various socioeconomic factors (i.e. population, per capita consumption volume, economic production structure and consumption structure) to consumption-based carbon footprint (CBF) of Beijing in total and decomposed into local production, domestic production and foreign production. It uncovers what causes the variation of CBF over time, as observed in Fig. 3.

We find that for total CBF, the improvement of carbon efficiency over the two periods is the major impetus of carbon mitigation, which strongly competed with the increasing effect from growing population and per capita consumption (Fig. 4a). Carbon emission intensity and per capita consumption have the similar absolute contribution to CBF but on two opposite directions (−292% and 314%, respectively) over 1985–2000. But the contribution of emission intensity (−453%) is much higher than that of per capita consumption (+255%) between 2000 and 2012, but the total CBF kept going up due to the significant positive effect from economic production structure (+219%). In comparison, the impact of consumption pattern on total CBF is relatively low except a decreasing effect (−16%) within 2000–2012. This indicates that improving carbon efficiency is still the most important way of reducing CBF, though this is offset by the carbon footprint increased by the raise of per capita consumption volume, the strongest driver for carbon emissions over time from a consumption-based perspective.

The change in emission intensity is the major factor that leads to a reduction in CBF from local production (Fig. 4b), which outruns the increased footprint caused by growth in population and per capita consumption combined over 2000–2012. This directly results in a reduction in the total local-production-related CBF during this period. Between 1985 and 2000, the impact of consumption structure on local CBF is almost negligible. But the situation twisted after 2000, when changes in the consumption structure strive to reduce carbon footprint (−110%), though its impact is still small compared to other factors. In terms of CBF originated from domestic and foreign production, we also observe a strong competition between emission intensity and per capita consumption level (Fig. 4c and d). But the contribution of lowering emission intensity is much smaller than that in local-production-related CBF. The main reason for this is the direct carbon emissions of urban sectors in Beijing have been reduced because of technology innovation and deindustrialization (e.g. elimination of high-carbon enterprises). In contrast, the industrial emissions of domestic and foreign market can only be reduced through improvement of production technology.

The most arrestive point is how carbon emission induced by domestic and foreign markets become the biggest fraction in the urban CBF after 2000. The increase in personal consumption (+73%) and the growth of population (+28%) are two main drivers of domestic induced CBF, same with the foreign induced CBF (+63% and 24%, respectively). During 2000–2012, Beijing's population has increased from 13 to 20 million, while the per capita GDP has also increased from \$4020 to \$14850 (which is almost 4 times higher). Variation in economic production structure is another important factor of increasing CBF. Regarding economic production structure change, a further decomposition of contribution by sector (Table A2) shows manufacturing industry is the biggest contributor during 1985–2000, while the supply of energy makes the biggest positive impact after 2000, followed by manufacturing and mining sector. This shows that optimizing economic structure in producing products can be very important for carbon footprint reduction in addition to the lowering of carbon intensity.

In an analogous way, Fig. 5 shows the contribution of socioeconomic factors to controlled carbon footprint (COF) of Beijing in total and decomposed into local, domestic and foreign productions. Overall, the decreasing effect in emission intensity (−247%) was offset by increasing effect of population and per capita consumption volume (+289% and +62%, respectively), resulting in a 39 Mt increment in COF during 1985–2000 (Fig. 5a). Between 2000 and 2012, due to the

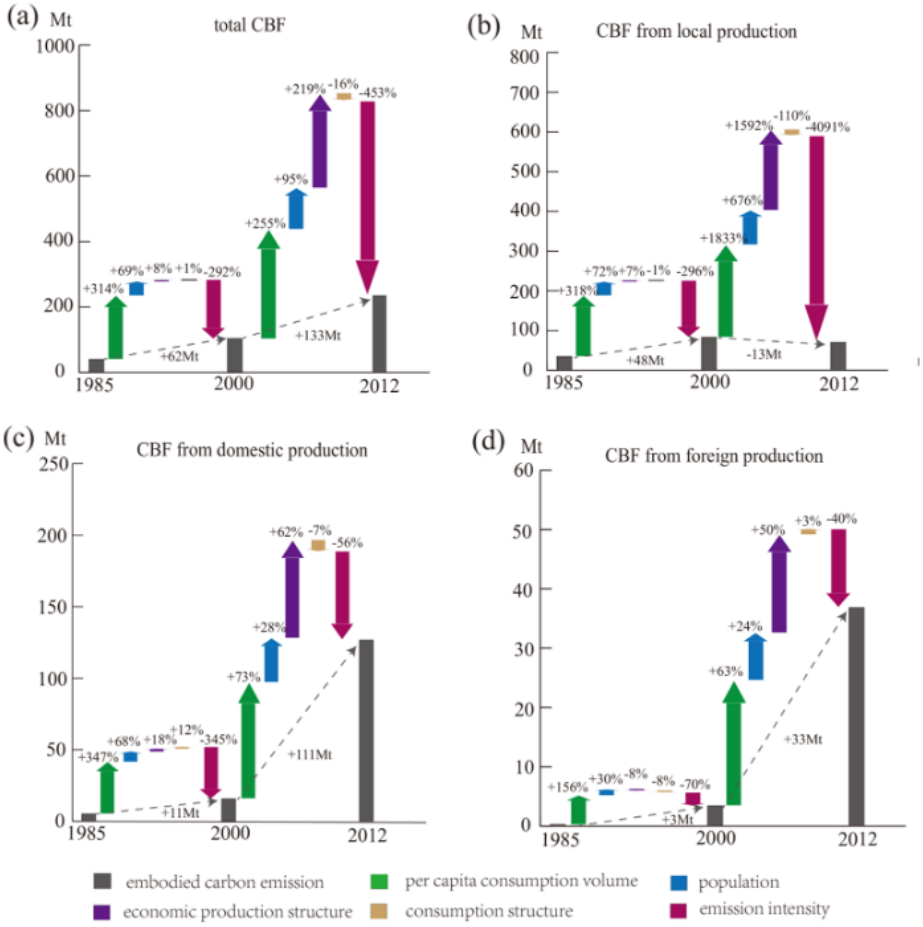


**Fig. 4.** Contributions of socioeconomic factors to consumption-based carbon footprint (CBF) (a) in total and decomposed into (b) local, (c) domestic and (d) foreign production.

continuous growth of population (+472%) and per capita consumption (+175%) and the variation in controlled structure rebounded (+458%), the changes in emission intensity (−979%) and consumption structure (−26%) are unable to reduce urban carbon footprint from a controlled perspective. The major reduction in emission intensity could have caused a reduction of local-production-related COF by 396 Mt (−3373%) during 2000–2012, exceeding the increasing effect from change in per capita consumption (+1407%) and population (+515%) (Fig. 5b). The carbon footprints controlled by final consumption from domestic and foreign imports went through a major growth during urbanization (Fig. 5c and d). During 2000–2012, increase in per capita consumption volume (+78%) and population (+30%) raise the COF by 39 Mt in despite of the decline in emission intensity (−60%). The foreign import related COF increased by 12 times driven by the changes in per capita consumption volume (+62%), population (+24%) and controlled structure (+57%).

Some notable differences between the indications by CBF and COF: (1) In certain cases, the directions of impact in terms of socioeconomic factors could be different. For example, CBF suggests the change in production structure adds to the increase in footprint by 8% over 1985–2000, but from a controlled perspective (COF), a reduction in footprint by 13% actually happens. But the more recent change in controlled structure always results in increase in carbon footprint. COF uncovers economic production has a subtle impact on the domination of carbon flows within the city, different from the full footprint induced by final consumption. (2) The consumption structure has a higher impact on COF than that on CBF. COF is very sensitive to the change in the pattern of urban consumption behaviors. This indicates carbon controlled by urban metabolism can be significantly reduced with people's turning to more low-carbon products. (3) The impact of consumption structure change on foreign import CBF suggests the situation is getting more high-carbon given its contribution switching from −8% to +3%, while from a controlled perspective an opposite change from +10% to −3% suggest the change in consumption structure has actually been towards a more low-carbon direction. (4) Different from CBF, COF suggests the supply of energy has a most significant impact on the controlled structure change over the whole time, while the impact from manufacturing sector twisted from negative to positive with 2000 as a watershed (Table A3). The reallocation of emission outside urban boundary does not mean a loss of control by the city. In fact, a huge amount of emission is still under controlled by a city through trade. Also, reallocation does not necessarily mean high-carbon or low-carbon pattern for a city. This is highly dependent on the economic structure and production technologies of both local and external regions.

### 3.4. Decomposed CBF and COF drivers by final demand categories

Fig. 6 shows the contributions of different final consumption categories to the socioeconomic drivers of CBF in different periods of time. Overall, rural consumption had the smallest impact on the CBF driven by each socioeconomic factor all along. The role of rural activities has been decreasing since the proportion of total CBF in 2000–2012 (~3%

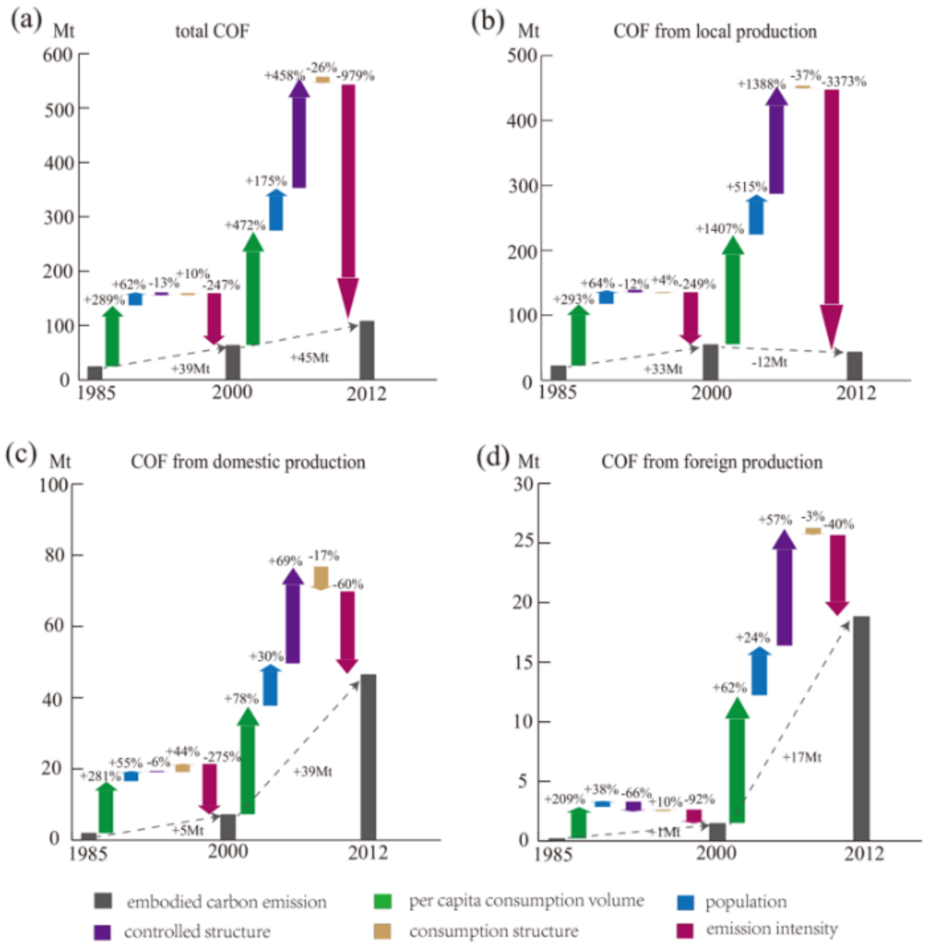


**Fig. 5.** Contributions of socioeconomic factors to controlled carbon footprint (COF) (a) in total and decomposed into (b) local, (c) domestic and (d) foreign production.

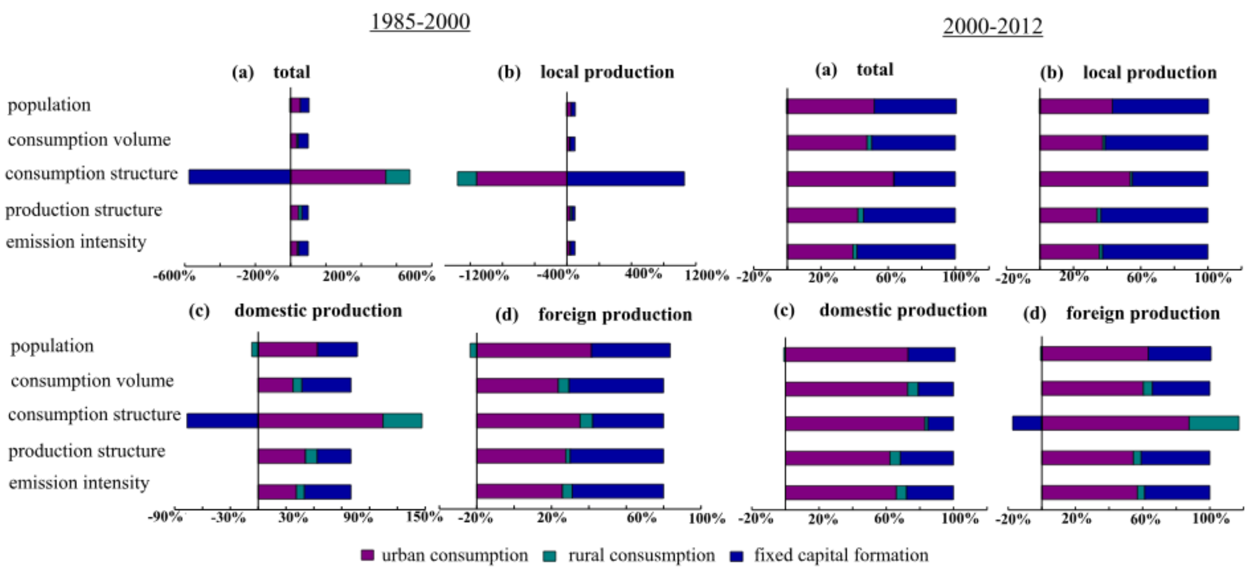


**Fig. 6.** Contribution of different final consumption categories to the socioeconomic drivers of CBF (a) in total, and decomposed into (b) local, (c) domestic and (d) foreign production.

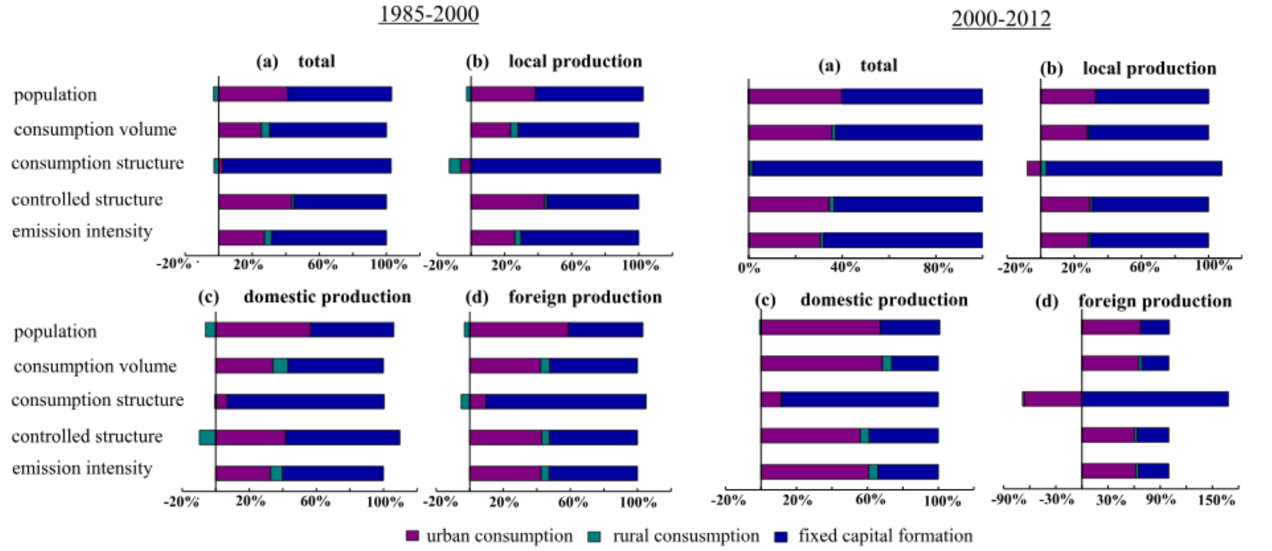


**Fig. 7.** Contribution of different final consumption categories to the socioeconomic drivers of COF (a) in total, and decomposed into (b) local, (c) domestic and (d) foreign production.

on average) is even lower than that over 1985–2000 (~15%). In contrast, urban consumption and fixed capital formation are most significant demand categories that pulled the CBF in terms of both different sources of production and different socioeconomic drivers. The ratio between urban consumption and fixed capital formation in contributing to the drivers of CBF tends to be stable over time. But some variations can be found during different stages of urban development. For example, urban consumption has a bigger contribution to the CBF driven by consumption structure over 2000–2012 than that before 2000. On the contrary, fixed capital formation has a more significant impact on the consumption structure in 1985–2000 than the period after 2000. However, fixed carbon formation has a growing influence on CBF driven by per capita consumption volume and population due to the increasing fixed assets in urban enterprises, government or households of Beijing. Also, urban consumption triggered higher carbon footprint from domestic and foreign import than that from local production. This is consistent with our findings from the total values of CBF in Fig. 3.

Fig. 7 shows the contributions of final consumption categories from a network-controlled perspective. Unlike CBF, the consumption structure mainly drives the total carbon footprint controlled by fixed capital formation, which explains > 90% of the total variation. This not only holds for local-production COF, but also for domestic and foreign import related COF. Moreover, the dominance of capital formation is also found in population-driven COF and per capita consumption-driven COF, which has a 1.5–2.0 times higher impact on COF than urban consumption. This is against the unconventional opinion that daily consumption of urban households plays a more important role. As uncovered by the controlled carbon footprint, for a city under fast urbanization, the accumulation of fixed assets could be more rapid than the increase in daily household consumption, thus controlling the effectiveness of urban carbon mitigation.

One important purpose of assessing controlled carbon footprint across boundaries is to know the important of optimizing the whole supply chains controlled by urban consumption rather than just the emission directly occurs inside a city. Another purpose is to provide information for guiding our consumption choices and behaviors of capital formation towards a more rational and low-carbon pattern (e.g. by adding suitable consumption tax to certain high-carbon products).

## 4. Concluding remarks

Cities are problems as well as solutions to global climate change in an urbanized world. The carbon inventory and modelling at city level are critical in addressing climate change and urban sustainability [53,54]. During the Great Acceleration, transferring to an urban style of livings will risk a notable increase of energy consumption and carbon emissions [55,56]. Only looking into the situation of a city within its territories will lead to an unsustainable pathway [18,19,57]. To avoid the environmental side effect of urbanization, it is important to include in-boundary and cross-boundary emissions in building low-carbon cities [58,59]. To properly address the urban impact on carbon emission, here we develop a system-based tracking approach for two types of urban carbon footprint, i.e. consumption-based carbon footprint and controlled carbon footprint. The contributions of various socioeconomic factors to the change of carbon footprints over 1985–2012 are quantified and decomposed into different sources of production (local, domestic and foreign). The major findings and implications:

(1) Both consumption-based and controlled carbon footprints of Beijing experience a major increase over the last three decades. The consumption-based carbon footprint in 2012 increased by nearly 284% compared with 1985, while controlled carbon footprint in 2012 increased by approximately 350% compared with 1985. On average, the consumption-based carbon footprint of Beijing grew by 7% each year, and controlled carbon footprint by 6% each year. About 40% of the carbon footprint in 1985 and 2000 and 55% in 2012 is not controlled within urban economy. This implicates that the controlled carbon footprint we proposed can be an important supplement in directing carbon mitigation actions given that consumption-based carbon footprint may beyond the city's capability of regulation.
(2) The consumption-based and controlled carbon footprints related to local production have decreased by 15% and 22%, respectively over 2000–2012, while the consumption-based and controlled carbon footprint from domestic and foreign imports has increased dramatically by 700% and 960% in the same period, triggered by the growth of urban residential consumption and fixed capital formation. The pressure of meeting huge urban demand is outsourced to domestic and foreign markets but still adds to the carbon footprint of the city. Reallocation of carbon emission from city to its

supporting regions has become a global challenge. This trend will most likely keep going and for a long time, the carbon footprints originated from domestic and foreign production can only be reduced by improving carbon efficiency in upstream production.

(3) The change in emission intensity is the major factor that leads to a reduction in consumption-based carbon footprint, which is unfortunately offset by the increased footprint caused by growth in population and per capita consumption. As with other studies [39] we also find that improving carbon efficiency is still the most important way of reducing footprint in current stage. But we specify that more potential of lowering carbon intensity holds in the whole production chains rather than the urban economy alone. Network control approach unveils key drivers of carbon emission that are actually regulated by a city as a consequence of its interactions with the rest of global economy. The changes in per capita consumption volume, population and controlled structure are three main drivers for the increase in controlled carbon footprint. The changing structure of economic production has a subtle impact on the carbon footprint controlled by the city, different from the full consumption-based footprint.

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## Appendix A

See Table A1–A3.

**Table A1**
The original sectors in the model and aggregated sectors for results interpretation.

| No. | Original sectors in the model | Aggregated sectors |
|---|---|---|
| S1 | Agriculture, forestry and aquaculture | Agriculture (S1) |
| S2 | Coal Mining, Petroleum and Natural Gas Extraction | Mining (S2-S4) |
| S3 | Ferrous and Nonferrous Metals Mining and Dressing | |
| S4 | Nonmetal Minerals Mining and Dressing | |
| S5 | Food Processing and Production | Manufacturing Industry (S5-S18) |
| S6 | Textile Industry, Garments and Other Fiber Products and Leather, Furs, Down and Related Products | |
| S7 | Timber Processing, Bamboo, Cane, Palm Fiber & 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 | Production and Supply of Electric Power, Gas and Hot Water | Supply of Electricity, Gas and Hot Water (S19) |
| S20 | Construction | Construction |
| S21 | Transportation, Storage, Post and Telecommunication Services | Transportation (S20) |
| S22 | Wholesale, Retail Trade and Catering Services, Restaurant, Renting and business services | Services (S22-S24) |
| S23 | Finance, insurance, scientific, environmental and technical services | |
| S24 | Public services and others services | |

**Table A2**
Sector contribution to production structure (L)-driven CBF.

| Unit: Mt | 1985–2000 | | | 2000–2012 | | |
|---|---|---|---|---|---|---|
| | U | D | F | U | D | F |
| Agriculture | 0.04 | 0.01 | 0.00 | 0.27 | -0.04 | 0.00 |
| Mining | 0.69 | 0.34 | 0.11 | 9.59 | 8.23 | 3.09 |
| Manufacturing industry | 1.93 | 1.22 | −0.16 | 104.36 | 7.39 | 3.14 |
| Supply of Electricity, Gas and Hot Water | −2.23 | −0.41 | −0.25 | 84.16 | 51.08 | 9.57 |
| Construction | −0.02 | 0.00 | 0.00 | 0.04 | 0.01 | 0.01 |
| Transportation | −0.41 | −0.06 | −0.01 | 5.85 | 2.38 | 1.01 |
| Services | 3.22 | 0.86 | 0.05 | 0.10 | 0.12 | 0.13 |
| SUM | 3.23 | 1.98 | −0.27 | 204.36 | 69.17 | 16.95 |

**Table A3**
Sector contribution to controlled structure (N)-driven COF.

| Unit: Mt | 1985–2000 | | | 2000–2012 | | |
|---|---|---|---|---|---|---|
| | U | D | F | U | D | F |
| Agriculture | −0.20 | −0.02 | −0.01 | 0.34 | −0.07 | 0.02 |
| Mining | 0.77 | 0.37 | 0.11 | 8.73 | 6.94 | 2.27 |
| Manufacturing industry | −1.35 | 0.48 | −0.39 | 107.26 | 7.01 | 3.39 |
| Supply of Electricity, Gas and Hot Water | −3.63 | −1.12 | −0.56 | 49.30 | 14.23 | 4.10 |
| Construction | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 |
| Transportation | −0.60 | −0.08 | −0.02 | 2.44 | 0.22 | 0.17 |
| Services | 0.92 | 0.13 | 0.00 | 0.53 | 0.07 | 0.13 |
| SUM | −4.09 | −0.25 | −0.86 | 168.61 | 28.41 | 10.09 |

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