Flow analysis of the carbon metabolic processes in Beijing using carbon imbalance and external dependence indices

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ABSTRACT: Maintaining urban systems consumes a large amount and variety of materials and leads to waste flows. Carbon is a basic element that intuitively characterizes the metabolic characteristics of urban resource consumption and pollution emission. In this study, we integrated the carbon metabolic flows among 18 metabolic actors and between these actors and the atmosphere, and calculated flows of material in many categories using empirically derived coefficients to estimate the associated carbon flows (emission and absorption). Taking Beijing as an example, we analyzed the dynamic changes in the carbon metabolism and the structural characteristics of material utilization. We defined two indices to characterize the metabolism (the carbon imbalance and external dependence indices), and identified key actors responsible for changes in the indices. The total carbon metabolism (inputs and outputs) increased by 64% and 200%, respectively, from 1995 to 2015, mainly driven by energy consumption, which accounted for more than 78% of the total. In addition, input growth was driven by food, accounting for up to 6% of the total. The carbon imbalance and external dependence indices increased to nearly two and four times their 1995 values, respectively, mainly due to the Manufacturing, Electricity and Heat Production, and Energy Conversion actors' demand for food or energy during the early part of the study period, and by the rapid growth of food or energy required by the Urban Life and Transportation actors. Identifying and comparing the key metabolic actors provided a novel way to analyze data to determine targets for carbon regulation and emission reduction measures for Beijing.

Keywords: urban metabolism; carbon metabolism; carbon imbalance; external dependence; Beijing

1. Introduction

A report released by the C40 Urban Climate Leadership alliance and the Carbon Disclosure Project Organization stated that cities accounted for 70% of global carbon emissions (KPMG, 2011). This results from high consumption of energy, food, and minerals by cities

(Musango et al., 2017), where the vegetation can only offset 8% of the emission that results from this consumption (Escobedo et al., 2010). This imbalance produces serious resource and environmental problems. Beijing, one of the largest of the C40 cities, has shown a 53% increase in the consumption of fossil fuels, biomass, and minerals since 1992 (Dai et al., 2017). The materials provided by Beijing's external environment increased from 30% of total consumption in 1992 to 60% in 2014, thereby exacerbating the dependence of production and life on external resources. These consumption problems have many causes, including low utilization ratios (Beijing's resource utilization efficiency in 2010 was only 1/8th of the highest level in the world) and high emission of pollutants. The surge of CO_2 emission (which increased to 2.5 times its 1995 level by 2015) attracted widespread attention (Zhang et al., 2015). At the same time, carbon absorption by vegetation was less than 10% of the emission, increasing the problems faced by Beijing's environment. These problems result from a disorder of urban carbon flows, including carbon transfers among the production and living sectors and carbon emission and absorption between sectors and the atmosphere. To support efforts to mitigate carbon emissions, it is necessary to consider these carbon flows from a metabolic perspective and analyze the degree of disorder in the carbon metabolism caused by each sector and its interactions with other sectors. The present study describes a new way to approach such studies by quantifying these imbalances.

Wolman (1965) first proposed the urban metabolism framework for studying shortages of water and the water and air pollution caused by urbanization. His framework provides a clear way to understand the material flows entering a city, and how human activities produce a series of wastes through consumption of these materials. Because the carbon in greenhouse gases is an important waste created by urban processes, it must also be accounted for. To find ways to cope with the global climate change created by this waste, researchers have increasingly focused on the theoretical perspective of urban carbon metabolism, which took urban metabolism as the theoretical framework and data base (Blečić et al., 2014; Kennedy et al., 2011; Pataki et al., 2006). Baccini (1996) was the first urban metabolism researcher to mention “carbon metabolism”. He divided the Swiss Lowland region into three metabolic actors: residential areas, farmland, and forest. He studied carbon fluxes among these actors and between them and the atmosphere, as well as the resulting changes in their carbon stocks. These fluxes included inputs of food and fuels, outputs of wastes, carbon transfers among the actors, and CO_2 emission and absorption between sectors and the atmosphere. Subsequently, carbon metabolism appeared in a report on the urban metabolism of Vienna, Austria (Obernosterer et al., 1998). Researchers divided the city into four metabolic actors: the atmosphere, humans, soils, and water. However, the carbon metabolic processes were similar to those of Baccini.

These early studies considered the socioeconomic actor as a “black box”, and did not analyze the carbon flows among the actors inside the box. More recent studies of urban carbon metabolism have focused on refinement of the metabolic actors. For example, researchers have defined metabolic sectors based on input–output tables and studied the embodied carbon transfers among a city’s production and living sectors (Zhang et al., 2014b; Zheng et al., 2016). Others have studied carbon from the perspective of production and consumption (Yang et al., 2015). Because these studies did not consider natural actors (e.g., vegetation growing inside a city), researchers added the natural actors by accounting for a city’s diverse land use types. Carbon metabolic actors have been divided into groups based on different land use types to allow analyses of the impact of land use planning on carbon emission (Blečić et al., 2014), and the spatial patterns of urban carbon emission and absorption have also been studied (Xia et al., 2016, 2017; Zhang et al., 2014a, 2016b). In addition, researchers have divided the actors among industrial sectors and land use types to study the sectoral distribution of urban carbon emission (Zhang et al., 2015). The most distinctive characteristics of this research are that it has examined multiple sectors and multiple materials, thereby providing increasingly deep insights into the urban metabolism. In particular, these studies have begun to reveal details of what happens inside the black box.

In summary, early studies of urban carbon metabolism covered the most important processes, including carbon transfers among actors, as well as carbon emission and sequestration. Nonetheless, the division of actors remained simplistic. Later research continued to refine the socio-economic actors, but did not always analyze carbon flows among the actors. As these flows within the black box are clearly important, researchers began looking for ways to analyze them.

To provide more precise insights, researchers have focused on smaller scale in urban range, or one metabolic actor of cities, or a kind of substance that contains carbon. To focus on smaller scale in urban range, Kellett et al. (2013) narrowed the range of their research to the community of south-central Vancouver, Canada, and refined the carbon metabolic actors into the buildings and the transportation, human, vegetation, and soil components. Lu et al. (2015) selected an ecological industrial park in Beijing, and divided it into six actors: energy supply, infrastructure, household, industrial and commercial, waste disposal, and artificial landscape. They analyzed the carbon transfers among these sectors and between the sectors and Beijing's external environment. To focus on one metabolic actor of cities, Ye et al. (2011) studied the relationships between the characteristics of household buildings and carbon emissions in Xiamen, China. Lee et al. (2016) studied energy consumption and carbon emission by different types of transportation in the city of Birmingham, U.K. To focus on a kind of substance that contains carbon, Lin et al. (2016) chose food, and studied the related carbon metabolic processes for Xiamen, China, including food consumption, human digestion and absorption, excretion, and waste disposal. Kennedy et al. (2010) divided the urban metabolic actors according to the end uses of different kinds of energy, and established a method for obtaining a greenhouse gas inventory. Their analyses of system components such as transportation and buildings, and the flow directions of food and energy, enriched our knowledge of urban carbon metabolism by identifying metabolic actors and the paths between them.

Research on carbon metabolic processes relies heavily on accurate carbon accounting. At present, the accounting system for carbon emission and absorption is relatively mature (Carney et al., 2009; IPCC, 2006; Zhang et al., 2015). As a result, researchers have quantified carbon flows among components of the urban system, including families, farmland, livestock breeding, and waste disposal. For instance, Rimhanen and Kahiluoto (2014) studied crops using empirically derived coefficients for carbon contents, field samples, and mass-balance equations, and analyzed the carbon distribution in flows related to crops, including the flows of food to humans, of carbon released into the atmosphere through fuel combustion, of feed to livestock, of straw into the soil, and of waste into the composting system. They also accounted for losses in the allocation process. On this basis, Zhang et al. (2016a) focused on livestock feed and used material-flow analysis to calculate the feed inputs, as well as the digestion, storage, and excretion of carbon by livestock in the animal husbandry system. Luo et al. (2008) studied the carbon flows related to food consumption by 1000 Beijing households using a survey and empirically derived coefficients. Baker et al. (2007) expanded the list of carbon-containing substances from food to include energy, paper, plastics, fertilizer, and the wastes generated from their consumption. They then used material-flow analysis and empirically derived coefficients to calculate the carbon flows of 35 suburban families. Based on Baker et al.'s method, Fissore et al. (2012) further expanded the number and scope of the investigated families, including 360 families from both rural and urban areas, and they accounted for the input and output carbon flows of "courtyards", including the inputs of dog droppings and the outputs of leaves and grass from lawn mowing.

These studies related to resource consumption, conversion processes, and subsequent waste production. Some researchers also focused on the subsequent waste disposal. Tonini et al. (2014) analyzed the carbon flow processes involved in refining and processing wastes, including waste inputs, pretreatment, screening, post-processing, recycling, and final disposal, and used elemental analysis (i.e., tracking the flows of an individual element) to quantify the carbon flows. Similarly, Zhou et al. (2015) studied the garbage disposal system using empirically derived coefficients to quantify the waste carbon stock and carbon inputs of the system. These studies provided methods and data for analyzing and quantifying the flows of carbon among the actors in an urban carbon metabolic system.

Early studies based on the urban metabolism theoretical framework divided the actors simply, using a relatively small number of actors. When researchers included more actors, they focused on the carbon emission and absorption based only on the flows between the actors and the atmosphere, or analyzed the flows transfer among actors. To provide greater resolution and a more holistic picture of a city's urban carbon metabolism, we chose Beijing, China, as an example, and refined the natural and socioeconomic metabolic actors into a greater number of categories with the goal of simultaneously quantifying the carbon metabolic flows among actors and between actors and the atmosphere. The current study is an extension of the previous study (Zhang et al., 2015). The data and accounting method for carbon emission and sequestration used can be seen in the previous study. Based on the available data, we accounted for carbon metabolic flows from 1995 to 2015, and analyzed the total carbon metabolism and the changes of the material flows and resulting structure of the metabolism. We also developed two new indicators: the Carbon External Dependence Index, which represents the ratio of external resources consumed to internal resources consumed, and the Carbon Imbalance Index, which represents the ratio of carbon emission to carbon absorption. Our goal was to detect and comprehensively evaluate any carbon metabolic disorders in Beijing's urban metabolism. We used this approach to identify the main actors that were responsible for the carbon metabolic disorders and support both efforts to optimize utilization of carbon-containing materials in

Beijing and the development of plans to reduce carbon emissions.

2. Material and methods

2.1. Analysis of and accounting for the carbon metabolic processes

Beijing's administrative boundary represents the dividing point between the city's internal and external environments. The internal environment excludes the natural components of the city that lie inside that boundary. We used the administrative boundary of Beijing as the system boundary in our analysis, and divided the metabolic actors into natural and socioeconomic categories based on the different types of land use and industrial actors. We identified a total of 18 metabolic actors (Table 1). Agriculture combines natural and socioeconomic attributes because it includes farmland, but from the perspective of defining actors, it is dominated by production activities, so we classified it with the socioeconomic actors. During our carbon accounting, we obtained data on the following metabolic substances: energy, minerals, disposable plastics, fertilizer, food, animal feed, wood, straw, biogas, and water. Since our goal was to quantify urban carbon transfers, we focused on the materials that were consumed over short periods (within a year), and excluded material consumption to create the urban carbon stock (e.g., durable goods such as buildings).

(Insert table 1 here)

The material flows within the model we defined for Beijing show obvious hierarchical relationships (Fig. 1). There are three main carbon-transfer chains: Agriculture, Forest, Grassland, and Bodies of Water absorb CO_2 from the atmosphere and convert it into organic matter, some of which is transmitted to humans and livestock through the food chain; the rest is transmitted to Manufacturing for further processing, and is finally consumed by humans and livestock. Fossil fuels and minerals are introduced into the urban metabolic processes through extraction from the internal environment (flows labeled *w*). Some of these materials enter the

Energy Conversion sector for further processing, and some of them directly enter a terminal consumption sector (i.e., any sector where they are consumed without undergoing additional processing). The external environment also provides products, which include semi-finished products such as fuel oil and naphtha, raw materials such as wood, and industrial products such as paper and plastic (z). Some of them enter the Manufacturing or Energy Conversion sectors, whereas others enter a terminal consumption sector, where they serve multiple socioeconomic actors. The metabolites produced by actors through their consumption of carbon-containing materials (i.e., waste products) are released directly into the natural metabolic actors or are processed (e.g., treated, recycled) before that release. These take the form of CO_2 emissions into the atmosphere, or discharge of solid wastes and wastewater into the Waste Disposal sector. Waste after disposal and treatment, along with some untreated waste, is finally discharged into Bodies of Water or the internal environment.

(Insert fig. 1 here)

Empirically derived coefficients for the carbon content of various materials can be used to convert the masses of materials into the corresponding carbon emission and absorption (equations 1 to 3):

Carbon transfer for food:

$$CT_{\mathrm{food}} = Mt \times TF \tag{1}$$

Carbon emissions for energy:

$$CE_{\mathrm{energy}} = Me \times EF \tag{2}$$

Carbon sequestration by Forest:

$$CS_{\mathrm{forest}} = A \times SF \tag{3}$$

Where CT_{food} represents the amount of carbon transfer among sectors in the form of food products, Mt represents the food quantity transferred between sectors, TF represents the food carbon coefficient (i.e., the proportion of carbon in the food), CE_{energy} represents the carbon emission between sectors and the atmosphere due to energy consumption, *Me* represents the energy consumption by a sector, *EF* represents the coefficient for energy carbon emission (i.e., the amount of carbon emitted per unit fuel consumption), CS_{forest} represents carbon uptake by tree photosynthesis, *A* represents the area of Forest, and *SF* represents the quantity of carbon uptake by photosynthesis per unit area. Supplemental Table S1 provides details of the calculations and the data sources. The data mainly come from the Beijing statistical yearbook (BMBS-SONBSB, 2016), China Energy Statistics Yearbook (ESD-NBSC, 2016), China Rural Statistical Yearbook (DRSEI-NBSC, 2016), China Environmental Statistics Yearbook (EBCEY, 2016), and the China Plastics Industry Yearbook (APPIC, 2015). All other references that we consulted are listed in the Supplemental materials, and particularly in Supplemental Table S1. Because most of the data we collected was based on Beijing's inputs and outputs, which were treated as a black box by the researchers who collected the data, they cannot be matched directly to the process paths shown in Figure 1. Therefore, we needed to define principles for distributing the flows represented by this data among the paths. The energy flows and food must be allocated according to Beijing's actual situation. In our analysis, the energy flows that we allocated were for coal, coke oven gas, coking products, gasoline, kerosene, diesel oil, and fuel oil (Table 2), as these are the primary forms of carbon-containing energy resources used in Beijing. In summary, the allocation process first allotted an input to the primary sector (labeled 1 in Table 2) until its needs were met, then any remaining amount was allocated to the secondary sector (labeled 2 in Table 2), and so on. For the distribution of food, we used the conservation of mass principle to calculate the flows. We assumed that local production was first allocated to meet local consumption needs and exports, with the remainder becoming outputs to the external environment. When the local production was insufficient to meet the local demand, the missing material was provided by inputs from the external environment. Details of distribution for other substance such as paper and plastic are provided in the Supplemental materials.

(Insert table 2 here)

2.2. Construction of the metabolic indices

To quantify the problems arising from urban carbon metabolic processes, we constructed a Carbon Imbalance Index (*CII*, which represents the ratio of carbon emission to carbon absorption) and a Carbon External Dependence Index (*CEDI*, which represents the ratio of external resources consumed to internal resources consumed). *CII* mainly accounts for the paths related to node 18 (the Atmosphere) of Beijing's carbon metabolic system. *CII* represents the carbon imbalance state in the vertical direction. As densely populated areas, cities mostly have actors with large carbon emissions, and have fewer actors with a small potential for carbon sequestration. Thus, carbon emission is generally far greater than carbon absorption in the vertical direction, resulting in a serious imbalance of the carbon metabolism. The larger the *CII*, the more serious the carbon imbalance. *CII* is calculated as follows (equation 4):

$$CII = \sum e_i / \sum s_i \quad (4)$$

where i is the carbon metabolic actor, e_i is the carbon emission by that actor, and s_i is the carbon sequestration (absorption) by that actor.

CEDI mainly accounts for the paths related to the external and internal environments. As highly open ecosystems, cities frequently exchange large amounts of carbon with their external environment. The processes in an urban carbon metabolism depend strongly on inputs from the external environment. Therefore, the ratio of inputs from the external environment to inputs from the internal environment reveals the degree of dependence of the urban metabolism on external resources. In view of the different metabolic pressures produced by the use of renewable and nonrenewable external resources, it is possible to assign different weights to these resources. For the sake of simplicity, we assumed that renewable resources had a weight of 0.5 and nonrenewable resources had a weight of 1.0. The greater the *CEDI*, the greater the dependence on the external environment. The formula for *CEDI* is as follows (equation 5):

$$CEDI = (0.5 \sum z_{i,r} + \sum z_{i,n} - 0.5 \sum y_{i,r} - \sum y_{i,n}) / \sum w_i \qquad (5)$$

where i is the metabolic actor, r is a given renewable resource, n is a given nonrenewable resource, $z_{i,r}$ is the quantity of carbon in renewable resources that is input to actor i from the external environment, $z_{i,n}$ is the quantity of carbon in nonrenewable resources that is input to actor i from the external environment, $y_{i,r}$ is the quantity of carbon in renewable resources that is output to the external environment from actor i, $y_{i,n}$ is the quantity of carbon in nonrenewable resources that is output to the external environment from actor i, and w_i is the quantity of carbon that is supplied by the internal environment from actor i.

Based on the two indices, we can identify which actors have increased their emissions or have had insufficient carbon absorption, leading to a carbon imbalance, and which actors depend on external resources to meet their demand. Based on the emission quantities, the absorption quantities, and the net external input, we identified the actors with the greatest carbon flows. Then, based on changes in *CII* and *CEDI* during different stages of our study period, we determined the contributions of each actor to Beijing's carbon metabolic disorders, and identified the actors with the greatest carbon flow and greatest change in this flow, as well as the actors that had a large carbon flow but small changes in this flow and the actors that had a small carbon flow but large changes in this flow. Finally, we determined whether there was consistency or a difference between pairs of key actors responsible for increases of the two indices, and used that comparison to determine the priority for managing or regulating these actors. That is, actors with a problem based on both indices should receive priority over actors with a problem based on only one of the indices, which in turn should receive priority over actors that have no problems based on either index. We then used the results of this analysis to develop objective management strategies to create a healthier carbon metabolism.

3. Results

3.1. Changes of the total carbon metabolism and its structure

The inputs and outputs of carbon for Beijing showed an overall growth trend from 1995 to 2015 (Fig. 2). The carbon inputs increased by 64% during the 21-year study period, but growth of the carbon outputs was faster (to more than 3 times the starting value by 2015, for an increase of more than 200%). Both inputs and outputs showed periods of growth and decrease. From 1995 to 2006, the carbon inputs and outputs increased by 49 and 74%, respectively. From 2006 to 2014, they decreased by 21 and 45%, respectively, and then increased by 39 and 240%, respectively, from 2014 to 2015.

These changes were driven mainly by energy flows, which accounted for more than 78% of the total throughout the study period, with inputs and outputs increasing by 98% and nearly 300%, respectively, compared with the 1995 values. Especially from 2014 to 2015, the input and output of energy (gasoline, diesel oil and liquefied petroleum gas) increased by 49 and 270%, which may be related to the expansion of the scope of the policy implementation for upgrading oil quality to reduce contaminants that would produce toxic emissions. As a result, there was huge deviation between 2015 and the other years (Fig. 2). The magnitude of the energy flows relative to the other flows resulted in the carbon inputs and outputs following the same trend as energy. The growth of total inputs was also driven by food imports. Although its initial proportion of the total flow was small (0.5%), it increased rapidly (to 18.8 times the 1995 value), accounting for 6% of the total by 2015. The inputs of plastic, paper products, water, wood, and fertilizer also increased rapidly (to as much as 7.4 times the 1995 value), and together, they accounted for 4% of the total flows. At the same time, the inputs of minerals and feed, which accounted for 20 and 5% of the total, respectively, in 1995 showed a decreasing trend; by 2015, they had decreased by 91 and 56%, respectively, and this slowed the growth of carbon inputs. Outputs of plastic and paper products increased to more than 14 times the 1995 value, water increased to 2 times the 1995 value, and food fluctuated, but ended by increasing to 10 times the 1995 value. However, because the cumulative proportion of the total for plastics, paper, water, and food was only 0.6%, they had little effect on the total carbon output. The amount of waste (about 1% of the total output) was also small, and its increase was only moderate (25%), so wastes had little impact on the carbon output. The decrease of mineral inputs partly offset the increase of carbon inputs. This is because it accounted for a relatively large proportion of the total input (20%) initially, during a period of large-scale construction in Beijing, and subsequently had a large decline, by 95%. In 2015, it only accounted for 0.2% of total inputs. The output of straw had little influence on the overall change, because its proportion of total outputs (about 0.05%) was small, and its decline (41%) therefore had little influence on the overall outputs.

(Insert fig. 2 here)

3.2. Analysis of *CII* and identification of the key actors

We assumed that the key actors were the ones that together accounted for 70% of the total emission. For all actors, the maximum carbon emission (by Manufacturing) was 800 times the minimum (by Fisheries), indicating a large difference among actors in their carbon emission. The average carbon emission of the key actors that accounted for 70% of the total emission was 9 times the average of the remaining actors that accounted for 30% of the total (i.e., almost one order of magnitude larger). This shows that the remaining 30% actors have small carbon emissions. Therefore, we select 70% as the criteria for identifying key actors. Thus, we believe it was acceptable to focus on the key actors. We applied the same rule to identify the key actors responsible for carbon absorption and net external inputs.

CII closely followed the trend for carbon emissions, since carbon absorption showed little change during the study period (Fig. 3). After 2011, *CII* was no longer synchronized with carbon emissions. The increase of *CII* resulted from the reduction of carbon absorption being greater than the decrease of carbon emissions. Overall, carbon emissions increased by 6% during the study period, whereas carbon absorption decreased by 38%. Beijing's *CII* nearly doubled, indicating that the magnitude of the imbalance increased greatly. However, there were different phases in its changes during the study period. *CII* increased by 86% from 1995 to 2007 (from 4.5 to its maximum value of 8.4), followed by a 17% decrease from 2007 to 2011 (from 8.4 to 7.0), and a 13% increase from 2011 to 2015 (from 7.0 to 7.9). This pattern was caused by changes in the flows related to the key actors (see Table 3).

(Insert fig. 3 here)

(Insert table 3 here)

From the direct flow diagram (Fig. 4) and Supplemental Table S2, we can see that all carbon metabolic actors had output paths to the atmosphere, whereas <25% of the actors had inputs from the atmosphere; the latter were Agriculture, Forest, Grassland, and Bodies of Water. Based on the key actors identified in Table 2, we can see that the carbon emission and absorption were relatively large for Manufacturing, Electricity and Heat Production, Transportation, Other Services, Urban Life, Rural Life, and Agriculture, and that these actors had a large contribution to the changes of *CII*. The share of carbon emission from Mining, Retail and Catering, and Waste Disposal was small (only 2% of the total in 1995), but Retail and Catering and Waste Disposal increased to 10 and 4 times their 1995 level, respectively, reaching 9% of the total in 2015. Mining was relatively stable before 2007, but then increased to 7.5 times this level by 2011, and then decreased by 95% until 2013. The contribution of these three actors to the changes of *CII* were relatively large.

The carbon emission by Manufacturing, Rural Life, and Agriculture decreased overall. Manufacturing, which accounted for 42% of the total in 1995, remained relatively stable, with only slight fluctuations before 2006. It then decreased, and was overtaken by Electricity and Heat Production in 2011. The carbon emission by Manufacturing in 2015 was only 20% of that in 2006 (and its proportion of the total decreased to 9%). The carbon emission by Rural Life decreased steadily before 2005. It increased significantly in 2006, reaching 1.6 times the value in 2005. It then decreased to 67% of its level in 2006. However, its share of the total during the study period was relatively stable, fluctuating between 4 and 6%. Agriculture (7% of the total in 1995) had a share close to that of Rural Life, but its share has been decreasing, with a decrease to 30% of its 1995 level by 2015 (when it accounted for 2% of the total). Electricity and Heat Production, Transportation, Other Services, and Urban Life all showed continuous emission growth. The proportion for Electricity and Heat Production (19%) was only smaller than that of Manufacturing in 1995. After 2011, it rose to first place (25%), and by 2015, it had increased to 1.4 times its 1995 value, and still accounted for about 25% of the total. Although the proportions of Transportation and Urban Life were both less than 10% in 1995, they increased to 6.7 and 1.4 times their 1995 values, respectively, by 2015, when they accounted for 18% and 16% of the total. Other Services increased twice as fast as of Electricity and Heat Production, but because its initial proportion was only 4%, its total remained less than 10% in 2015.

Agriculture had the largest carbon absorption (accounting for 49% of the total), but with the area of farmland (i.e., the Agriculture actor) shrinking, its carbon uptake decreased year by year. In 1999, it was overtaken by Forest, and in 2003, it dropped to 35% of its 1995 value (accounting for only 26% of the total). From 2003 to 2008, it increased again, reaching 1.5 times its value in 2003 (and accounting for 35% of the total). Then it decreased again, reaching only half of its value in 2008 (and accounting for 22% of the total). Forest had relatively large carbon absorption, but its total absorption did not change much during the study period. It decreased by less than 4%. However, with carbon absorption by Agriculture decreasing, the proportion of Forest carbon absorption increased from 42% to 65%.

(Insert fig. 4 here)

3.3. Analysis of *CEDI* and identification of the key actors

CEDI generally increased, reaching 4 times its 1995 value by the end of the study period, though with some fluctuation caused by the influence of inputs from both the external and the internal environments (Fig. 5). From 1995 to 2004, *CEDI* showed the opposite trend from that for internal inputs, but *CEDI* fluctuated more significantly than these inputs. By 2000, the internal inputs had decreased to half their 1995 value, while *CEDI* increased to 2.6 times its 1995 value, mainly due to the large increase (by 48%) of net external inputs. From 2004 to 2010, *CEDI* showed fluctuations that were similar to those of net external inputs, reaching 2.9 and 1.2 times the 2004 value. However, *CEDI* fluctuated more than the net external inputs. This was mainly due to the 57% decrease in the internal inputs during this period. From 2010 to 2015, *CEDI* showed a synchronous downward trend similar to that for the net external inputs (decreasing by 14 and 21%, respectively), mainly due to the relatively stable internal inputs. The changes in external and internal inputs resulted from changes in the inputs of key actors (see Table 4).

(Insert fig. 5 here)

(Insert table 4 here)

From the direct flows in Figure 4 and Supplemental Table S2, we can see that except for Waste Disposal, Grassland, and the Atmosphere, the other carbon metabolic actors (which accounted for 83% of the 18 actors) all had carbon transfers with the external environment, but only Mining received carbon inputs from the internal environment. Among the key actors identified in Table 4, the net external inputs for Manufacturing, Electricity and Heat Production, Energy Conversion, Transportation, and Urban Life were large, so their contributions to the changes of *CEDI* were also great. Although Retail and Catering and Animal Husbandry had a relatively small share of total inputs in 1995 (11% of the total), both actors changed greatly during the study period. Retail and Catering has grown steadily, reaching 29 times the 1995 value by 2015. Its proportion also increased during this period, from 0.5% to 9.0%. Animal Husbandry decreased by 54% (so its share decreased from 10% to 3%), with frequent fluctuations. It decreased greatly from 1995 to 1996, reaching 1.5 times its original value in 1996. Between 1996 and 2003, it grew to 4 times its 1996 value, and from 2003 to 2015, it decreased by 30% compared with its 2003 value. Among the actors with large net external inputs, Manufacturing, Energy Conversion, and Electricity and Heat Production were especially prominent. Manufacturing's net external inputs generally decreased, whereas those of Electricity and Heat Production and of Energy Conversion increased continuously. Net external inputs for Transportation and Urban Life also increased year by year, but their total contribution remained less than those of Manufacturing, Energy Conversion, and Electricity and Heat Production.

For Manufacturing, the initial net external input accounted for one-half of the total, and this proportion remained relatively stable until 2007. After 2007, it began to decrease greatly, and its contribution was exceeded by Energy Conversion and by Electricity and Heat Production in 2010. In 2015, it decreased to less than 25% of its 2007 value (and its proportion of the total decreased to 11%). This resulted mainly from the large decrease of nonrenewable resources such as energy and minerals, which had the largest share of its inputs (accounting for 52 and 46%, respectively, of the total in 1995). By 2015, they had decreased to 24% and 6% of their 1995 values, respectively, accounting for 48% and 8% of the total. Renewable resources such as the raw materials for production of paper and food accounted for less than 2% of the total in 1995, but they increased year by year, reaching 8 times their 1995 value and with their share of the total rising to 44%. Net external inputs for Energy Conversion accounted for 28%

of the total in 1995, which was less than those of Manufacturing and Energy Conversion. Its inputs increased continuously before 2010, reaching 2.6 times its 1995 value and surpassing the contributions of Manufacturing and of Electricity and Heat Production. Thereafter, it decreased by 19% and its contribution was exceeded by that of Electricity and Heat Production. However, Manufacturing still accounted for 25% of total inputs by 2015. This resulted from changes in the inputs of petroleum and coal products, which accounted for 63 and 37% of the total input, respectively. Oil products increased (by 96% compared with the 1995 level), whereas coal products decreased (by 97%). In 2015, these two inputs accounted for 94% and 0.6%, respectively, of the total inputs. Figure 4 shows that about 40% of the carbon input for Energy Conversion was exported to the external environment through simple packaging (i.e., there was no change in the energy form). The amount of exported carbon remained relatively stable during the study period. However, it increased sharply in 2015, reaching 5 times its 2014 level. Its proportion of the total also increased to 76%. Another part of the carbon, accounting for about 50%, flowed to Manufacturing, Transportation, Urban Life, and Electricity and Heat Production. This flow fluctuated from 2007 to 2013. Its maximum value appeared in 2010, and represented a 70% increase compared with the value in 2007. The last 3% of the carbon came from discharges during production processes. Therefore, the external dependence of Energy Conversion mainly contributed to the external environment, or served the consumption of other actors.

Although the initial net external input of Electricity and Heat Production in 1995 accounted for only 9% of the total, it increased to 24% (nearly 3 times its original value) by 2015, and was second only to Energy Conversion. This resulted mainly from changes in the inputs of coal and natural gas. Coal accounted for 98% of the total in 1995, and this share increased until 2008, reaching 4 times its initial value. Thereafter, it decreased rapidly (by 73%), and accounted for only 29% of the total in 2015. In contrast, natural gas was introduced in 1997 and increased year by year, reaching 3382 times its 1997 value by 2015, when it exceeded the contribution of coal, with its share reaching 70%. The net external inputs of Transportation and Urban Life accounted for 3 to 4% of the total in 1995, but increased to about half of the value for Electricity and Heat Production in 2015, representing growth to 5.7 and 2.4 times the 1995 value, respectively. The growth of net external inputs for Transportation was mainly affected by secondary energy from petroleum, such as gasoline, diesel, and kerosene, which accounted for 89% of the total energy consumption, and which increased to five times the 1995 value by 2015. The input growth for Urban Life mainly resulted from increased consumption of food and plastics, reaching 12 and 10 times the 1995 values, respectively, and from a 48% increase in energy consumption, which accounted for more than half of the total net external inputs.

Figure 4 shows that, in addition to Electricity and Heat Production, Mining also contributed more than 20% of the carbon that was exported to the external environment. About 63% of the output carbon was exported to the external environment. The exported carbon decreased by 48%, with some fluctuation, during the study period. The carbon (about 32% of the total) that was output to Electricity and Heat Production, Energy Conversion, and Manufacturing also decreased by 72%, with fluctuation. The rest of the carbon (4%) was discharged during production by Mining. The amount of carbon that comprised external inputs was less than the amount of carbon output to the external environment. The input carbon mainly came from the internal environment and decreased by 64% from 1995 to 2015, with some fluctuation. This trend was mainly affected by the 55% decrease of the input energy, which accounted for more than 70% of total inputs. In addition, the 83% decrease of mineral inputs, which accounted for less than 30% of inputs during the study period, also led to decreased inputs from the internal environment.

4. Discussion

Early studies of urban carbon metabolism mostly focused on carbon emission and carbon absorption based on carbon flows between components of the metabolic system or between actors and the atmosphere, with relatively simple partitioning of actors into categories such as Farmland, Forest, and Human Settlements (Baccini, 1996). Much of the carbon absorbed by Agriculture was considered to be rapidly biodigested, decomposed, and released into the atmosphere (Metz, 2007), and this may be why most of this research did not consider the agricultural absorption of carbon (Rimhanen and Kahiluoto, 2014). However, the contribution of Agriculture to carbon absorption cannot be neglected. The carbon output of agricultural products in China's Guangyuan City amounted to only 25% of crop production, and this offset 17 to 27% of the carbon emission from energy consumption (Hao et al., 2015). This is why the present study accounted for both obvious actors involved in carbon absorption (Forest, Grassland) and less obvious actors (Agriculture, Bodies of Water). The research on carbon flows among sectors mainly focused on the production and distribution of crops (Rimhanen and Kahiluoto, 2014), the consumption of family foods (Luo et al., 2008), consumption of energy, paper products, plastics, and other materials related to the family life (Fissore et al., 2012), and finally on the disposal of household garbage (Tonini et al., 2014).

The relevant household consumption research related to flows among actors did not reflect differences in the characteristics of the urban and rural actors. Therefore, in the present study, we divided the domestic actors into urban and rural actors, thereby revealing differences in their energy consumption structures caused by changes in the standard of living and population changes during China's rapid urbanization during the past several decades. Research on the integrated carbon flows among sectors and between sectors and the atmosphere has been complicated by difficulty in defining the main actors appropriately (Obernosterer et al., 1998). In their study of the carbon metabolism of Vienna, Chen and Chen (2012) refined the industrial actors into Energy Production, Construction, Agriculture, and Services. However, they only defined Atmosphere, Bodies of Water, and Soil as natural actors, so their division of the system into actors remained relatively coarse. In the present study, we divided the actors more finely, including our division of the broad "industries" group into Manufacturing, Mining, Electricity and Heat Production, and Energy Conversion, and subdivided the Services sector into Transportation, Retail and Catering, and Other Services to reflect the differences in carbon metabolism among these different functional areas. To help quantify potential problems with a city's carbon metabolism, we developed the *CII* and *CEDI* indices. These improve our ability to quantitatively and comprehensively describe problems with an urban carbon metabolism and reveal relationships among actors, thereby providing better scientific support for ecological management decisions.

Population aggregation due to urbanization, rapid economic development, and limited availability of natural resources in a city's internal environment have led many cities around the world to rely heavily on inputs of external resources (Pulselli et al., 2007; Zhang et al., 2009b). However, the degree of dependence on these external resources varies, and most representations use the proportion of total inputs from the external environment (Fang et al., 2017; Lei et al., 2016; Qi et al., 2017; Zhang et al., 2009a), or use the ratio of external inputs to consumption (Wu and Chen, 2017). Like the latter ratio, *CEDI* reflects the structure of the supply of inputs (the ratio of external to internal sources), so both can reflect the contribution of internal and external resources. However, our index represents an explicit comparison of the external and internal resources, which is only implicit in the index developed by Wu and Chen. In a previous study, emergy synthesis revealed that Beijing's dependence on external resources has increased, with a growth of 16% (despite fluctuations) from 1990 to 2004 (Zhang et al., 2009a). This agrees with the present results, in which we demonstrated that Beijing's dependence on its external environment fluctuated greatly, but increased to nearly 4 times its

1995 value by 2015.

The increase was larger in the present study for at least two reasons: first, the present study covered a 10-year-longer period, during which time imports of external resources have increased continuously, and second, the value of an index obtained by means of emergy synthesis is highly sensitive to the conversion factors used to convert material flows into emergy values. Previous studies have shown that only one-half of the CO_2 emission worldwide by human activities is absorbed by the land and ocean, so the carbon imbalance is prominent (Miller, 2008). When the carbon imbalance is represented, the ratio of carbon absorption to carbon emission is usually adopted. In this study, we used the reciprocal of this value, as that better reflects the severity of the changes in *CII*. Previous research showed that China's *CII* ranged from 28% to 37% (Piao et al., 2009), whereas urban *CII* is only 10% (Obernosterer et al., 1998; Zhao et al., 2014). If the algorithm used in the Obernosterer and Zhao studies had been used in the present study, then urban *CII* would increase to 22%. The reason why urban *CII* is low relative to the national *CII* (Piao's value) is that the urban metabolism is highly concentrated, rather than spread out at a national scale, and the vegetation cover in cities is very low compared to the cover on a national scale, which includes large vegetated areas outside cities. The net carbon inputs and emissions are important factors that affect *CEDI* and *CII*, respectively. Figure 6a shows that the factors that define the two indices showed obvious synchrony in their growth trend (about 37% growth) and their reduction trend (about 18% reduction). Because carbon emissions are produced during resource consumption, and most of the carbon resource depended on external inputs, the synchronous changes of carbon net inputs and emissions reflected how actors increase carbon emission during exchanges among actors.

The activities of actors, and especially the key actors, lead to heavy urban dependence on external resources, leading to a carbon imbalance. We summarized and compared three levels of key actors for *CEDI* and *CII* to help prioritize the key actors for efforts to reduce their carbon emission (Table 5). We used the following principles for this division: actors at the first level based on both indices receive a level I priority, actors at the first level based on only one of the indices receive a level II priority, actors that are at the second level based on either index receive a level III priority, actors that are at the third level based on both indices receive a level IV priority, and actors that are at the third level based on only one of the indices receive a level V priority. On this basis, Electricity and Heat Production, Transportation, Urban Life, and Manufacturing, which have large carbon imbalances and high external dependence, receive the highest priority. In particular, Transportation's carbon emission is large and growing rapidly, mainly due to a rapid increase in private car ownership (nearly half of Beijing's total vehicles). Although the government has implemented a series of measures to mitigate this problem, such as limiting the days on which a given vehicle can drive and limiting the number of vehicle permits, it has been unable to curb the growth trend for Transportation carbon emission. Currently, to receive permission to buy a car in Beijing, drivers must participate in a registration lottery. Only winners are granted permission to buy a car. Although the proportion of winners who receive permission to purchase a high-efficiency vehicle (e.g., electric, hybrid, hydrogen) increased to 40% of the total registrations in 2017, the number of winners still cannot meet the demand. Therefore, development of electric and hybrid vehicles, as well as fuel cell vehicles, must be encouraged, and measures such as limits on the number of new licenses and the implementation of special roads reserved for use by these vehicles should be used to encourage replacement of old, energy-inefficient vehicles that consume fossil fuels.

Actors at levels II and III include Agriculture, Rural Life, Energy Conversion, Mining, and Forest. These priorities include two actors with strong carbon absorption (Agriculture and Forest). The reduction of the Agriculture area and decreasing agricultural production per unit area (a decrease by 25% during the study period) has resulted in greatly decreased agricultural carbon absorption. This has occurred mainly because of the rapid development of Beijing, leading to conversion of agricultural land into built-up land. Agriculture must become more modern and intensive to counteract this decrease in its production; for example, real estate development in farmland areas should be curtailed, and solutions such as three-dimensional agriculture ("vertical farms") should be used to increase production and agricultural carbon uptake per unit area. Beijing's Forest actor has considerable potential for additional development. Currently, 62% of the city's forest is not healthy. It would become possible to increase the average carbon storage capacity of these trees by 100% if more than 90% of the forest was restored to a healthy state, so it is urgent to find ways to improve forest health.

Although actors at levels IV and V (Retail and Catering, Waste Disposal, Animal Husbandry, and Mining) have a smaller impact on the overall carbon metabolism, they should not be neglected. This is particularly true for Waste Disposal, which can both decrease inputs of materials by recycling materials and preventing outputs of materials as wastes. Though such changes may be individually small, they may add up to a significant cumulative effect.

(Insert table 5 here)

The changes in carbon flows through the key actors has been driven by changes in Beijing's socioeconomic scale and intensity, thereby affecting the *CEDI* and *CII* indices. Figure 6a shows that when the population, GDP, per capita GDP, and built-up area increased continuously (a minimum growth of 73%), both the carbon emissions and net inputs of the 18 actors showed an initial increase (about 37% growth) and then a decrease (about an 18% decrease. This shows that the efficiency of Beijing's carbon metabolism has improved during the city's development. This is mainly due to a significant decrease in the proportion of industries with a high carbon emission intensity. For instance, the proportion of industry (including Manufacturing, Mining, Electricity and Heat Production, and Energy Conversion) decreased from 35% to 16% during the study period. Simultaneously, the proportion of industries with a low carbon emission intensity increased greatly. For instance, the proportion of industry accounted for by Other Services (i.e., service industries other than Transportation and Retail and Catering) increased from 31.5% to 62.9% during the study period. This indicates the upgrading and transformation of Beijing's industrial structure.

During the same period, the consumption of coal, which has a high carbon emission coefficient, decreased from 55% to 10% of energy consumption by Industry and Other Services, while the proportion of natural gas, which has a low carbon emission coefficient, increased from less than 0.3% to 20%, suggesting optimization and adjustment of Beijing's energy consumption structure. In fact, due to the 2008 economic crisis, emission of greenhouse gases has decreased globally (Feng et al., 2015). This has also reduced Beijing's carbon imbalance due to decreasing carbon emissions, as we can see from the present results. By comparing the trends for *CII* and *CEDI* with the trends for population, GDP, per capita GDP, and the built-up area index, we can see that *CII* increased by 74% (with fluctuation) and *CEDI* increased to 4 times its 1995 value during a period when GDP and per capita GDP increased to 15 and 8.8 times their 1995 values. However, the rates of population growth and of expansion of Beijing's built-up area have been lower than the increase in *CEDI*; the population has grown exponentially, at about the same rate as *CII* (73%), and growth of the built-up area was about 2.6 times that of *CII*. These results suggest that Beijing's carbon metabolism has not increased synchronously with the material base while creating GDP and serving the city's population. We found that *CEDI* was strongly correlated with population, GDP, and per capita GDP ($r > 0.87$, $p < 0.05$), and moderately strongly correlated with the area of the city ($r = 0.76$, $p < 0.05$), indicating that the population growth, economic development, and improved living standards have either increased Beijing's dependence on its external environment, or failed to prevent this increase. Similarly, *CII* was moderately strongly correlated with population, GDP, and per capita GDP ($r = 0.57$ to 0.64, $p < 0.05$), and strongly correlated with the built-up area ($r = 0.91$, $p < 0.05$), indicating that expansion of the built-up area has either increased the carbon imbalance or failed to prevent its increase.

(Insert fig. 6 here)

5. Conclusions

In this study, we integrated carbon metabolic flows, both among sectors and between sectors and the atmosphere, to establish an analytical framework for improving the study of urban carbon metabolic processes. We refined our model of the urban system by defining 18 actors, thereby providing deeper insights into their roles in the overall metabolism and their relationships with each other. In addition, based on the relationship between the natural actors and the atmosphere, and between the whole city and its external environment, we established two new indices to quantify the carbon imbalance and external dependence, thereby revealing two complementary dimensions of the problems that arise in an urban carbon metabolism.

We found that Beijing's carbon inputs and outputs increased greatly from 1995 to 2015. This was mainly driven by greatly increased energy consumption, both in absolute terms and as a percentage of the total carbon flows, and by increased food consumption due to the rapid population increase that has accompanied urbanization. *CII* and *CEDI* both increased greatly, indicating increasing problems with Beijing's carbon metabolism. These increases resulted mainly from high demand for energy and minerals by the Manufacturing, Electricity and Heat Production, and Energy Conversion actors early in the study period, and by rapid growth of demand for food and energy by Urban Life and Transportation.

One limitation of the present analysis is that it concentrated on flows, but did not account for changes in carbon stocks over time. Beijing's rapid urbanization, and particularly the construction of the built-up area, will have led to large accumulation of carbon stocks that should be quantified in future research, as they will influence future carbon flows. Future research should also identify processes that promote and inhibit carbon flows and the resulting changes in the carbon stock. Identifying these processes will let managers consider how to modify the processes to encourage a more balanced metabolism. The improved knowledge provided by these analyses will build on the present results to support the development of an ecological network model that will provide additional management insights.

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List of Tables:

Table 1

The actors in Beijing's carbon metabolic system.

Natural Actors	Socioeconomic Actors
the Atmosphere, Forest, Grassland, Bodies of Water	Agriculture, Animal Husbandry, Fisheries, Manufacturing, Mining, Electricity and Heat Production, Energy Conversion, Construction, Transportation, the wholesale and retail sector (which includes accommodation and catering; hereafter, Retail and Catering), Other Services, Waste Disposal, Rural Life, Urban Life

Table 2

The distribution of different carbon-containing energy types within Beijing's carbon metabolic system. In terms of distribution of these flows among the sectors, 1 represents the sector with the highest priority, 2 represents the second priority, and so on.

Kind of energy	Priority for energy distributions					Investigated objects
	1	2	3	4	5	
Coal	Mining	Export/output	Electricity and Heat Production	Energy Conversion	Manufacturing	Jingmei Group
Coke oven gas	Manufacturing	Urban Life	Retail and Catering	Other Services	Electricity and Heat Production	Beijing Coking Plant
Coking products	Output/export	Manufacturing	Electricity and Heat Production	Mining	——	Beijing Coking Plant
Gasoline	Energy Conversion	Transportation	Urban Life, Rural Life	Retail and Catering, Other Services, Manufacturing, Construction, Agriculture	Output/export	Beijing Yanshan Petrochemical Company
Kerosene	Energy Conversion	Transportation	——	——	——	Beijing Yanshan Petrochemical Company
Diesel oil	Energy Conversion	Transportation	Urban Life, Rural Life	Mining, Electricity and Heat Production, Construction, Agriculture, Manufacturing	Output	Beijing Yanshan Petrochemical Company

Fuel oil	Energy Conversion	Electricity and Heat Production	Manufacturing	Retail and Catering, Other Services, Transportation, Construction, Mining	Output	Beijing Yanshan Petrochemical Company

Table 3

Key actors (the actors that together accounted for 70% of carbon emission) that most strongly affected trends in the carbon imbalance index (*CII*) for specific periods and for the study period as a whole. Underlined actors changed in the opposite direction from the overall trend shown in Figure 3. "Levels" represent the major actors (level 1) and minor but still significant actors (levels 2 and 3).

	1995 to 2007	2007 to 2011	2011 to 2015	1995 to 2015	Key actors
Actors responsible for high carbon emission	Manufacturing, Electricity and Heat Production, Transportation, Other Services, Urban Life, Rural Life, Agriculture	Manufacturing, Electricity and Heat Production, Transportation, Other Services,	Manufacturing, Electricity and Heat Production, Transportation, Other Services, Urban Life	Manufacturing, Electricity and Heat Production, Transportation, Other Services, Urban Life, Rural Life, Agriculture	Manufacturing, Electricity and Heat Production, Transportation, Other Services, Urban Life, Rural Life, Agriculture
Actors responsible for high carbon absorption	Agriculture, Forest	Forest, Agriculture	Forest, Agriculture	Forest, Agriculture	Forest, Agriculture
Overall trend for carbon emission	Increase	Decrease	Decrease	Increase	—
First level	Transportation, Electricity and Heat Production, Other Services, Urban Life, Manufacturing	Manufacturing, Transportation, Urban Life	Electricity and Heat Production, Manufacturing, Agriculture, Urban Life, Rural Life, Transportation	Transportation, Electricity and Heat Production, Urban Life, Other Services, Agriculture, Manufacturing	Transportation, Electricity and Heat Production, Urban Life, Other Services, Manufacturing, Agriculture, Rural Life

Third level	Retail and Catering	Mining	Mining, Waste Disposal	Retail and Catering, Waste Disposal	Retail and Catering, Waste Disposal, Mining
Overall trend for carbon absorption	Decrease	Increase	Decrease	Decrease	—
First level	Agriculture	Agriculture	Agriculture	Agriculture	Agriculture
Second level	—	—	—	—	Forest

Table 4

Key actors (the actors that together accounted for 70% of net carbon input) that influenced the changes in the carbon external dependence index (*CEDI*) for Beijing's carbon metabolic system for specific periods and for the study period as a whole. Underlined actors changed in the opposite direction from the overall trend shown in Figure 5. "Levels" represent the major actors (level 1) and minor but still significant actors (level 2 and 3).

	1995 to 2004	2004 to 2010	2010 to 2015	1995 to 2015	Key actors
Actors responsible for large net inputs of carbon from the external environment	Manufacturing, Energy Conversion, Electricity and Heat Production	Manufacturing, Energy Conversion, Electricity and Heat Production	Manufacturing, Energy Conversion, Electricity and Heat Production, Transportation, Urban Life	Manufacturing, Energy Conversion, Electricity and Heat Production, Transportation, Urban Life	Manufacturing, Energy Conversion, Electricity and Heat Production, Transportation, Urban Life
Actors responsible for large inputs of carbon from the internal environment	Mining	Mining	Mining	Mining	Mining
Overall trend for net external inputs	Increase	Increase, but with fluctuation	Decrease	Increase	—
First level	Manufacturing, Electricity and Heat Production, Energy Conversion, Transportation	Electricity and Heat Production, Energy Conversion, Transportation, Urban Life, <u>Manufacturing</u>	Manufacturing, Electricity and Heat Production, Energy Conversion, Transportation, <u>Urban Life</u>	Electricity and Heat Production, Energy Conversion, Transportation, Urban Life, <u>Manufacturing</u>	Manufacturing, Electricity and Heat Production, Energy Conversion, Transportation, Urban Life
Third level	Other Services	Retail and	—	Retail and	Retail and

		Catering, Animal Husbandry		Catering, Animal Husbandry	Catering, Animal Husbandry
Overall trend for internal inputs	Fluctuating	Decrease	Decrease	Decrease	Decrease
First level	Mining	Mining	Mining	Mining	Mining

Table 5

Levels of the actors in Beijing's carbon metabolism (i.e., priorities for action to reduce carbon emission). *CII*, the carbon imbalance index; *CEDI*, the carbon external dependence index; Priority, the priority for efforts to regulate emission or increase sequestration by the metabolic actors.

<table>
<tr><th></th><th>CII</th><th>CEDI</th><th colspan="2">Priority level</th></tr>
<tr><td rowspan="2">First level</td><td rowspan="2">Manufacturing, Electricity and Heat Production, Transportation, Other Services, Urban Life, Rural Life, Agriculture (emission and sequestration)</td><td rowspan="2">Manufacturing, Electricity and Heat Production, Energy Conversion, Transportation, Urban Life, Mining(input from the internal environment)</td><td>Level I</td><td>Transportation, Electricity and Heat Production, Urban Life, Manufacturing</td></tr>
<tr><td>Level II</td><td>Other Services, Energy Conversion, Agriculture (emission and sequestration), Rural Life, Mining (input from the internal environment)</td></tr>
<tr><td>Second level</td><td>Forest (sequestration)</td><td>—</td><td>Level III</td><td>Forest (sequestration)</td></tr>
<tr><td rowspan="2">Third level</td><td rowspan="2">Retail and Catering, Waste Disposal, Mining</td><td rowspan="2">Retail and Catering, Animal Husbandry</td><td>Level IV</td><td>Retail and Catering</td></tr>
<tr><td>Level V</td><td>Waste Disposal, Mining, Animal Husbandry</td></tr>
</table>

List of Figures:

Fig. 5. Changes in the carbon external dependence index (*CEDI*) for Beijing's carbon metabolic system from 1995 to 2015, and contributions of the dependence on internal and external resources to the changes.

Fig. 6. (a) The changes of net carbon inputs and emissions in relation to changes in the socioeconomic indicators (GDP, per capita GDP, population, and built-up area) during the study period.

(b) The correlations (Pearson's *r*) between the socioeconomic development indicators and the carbon indicators (*CEDI* and *CII).*

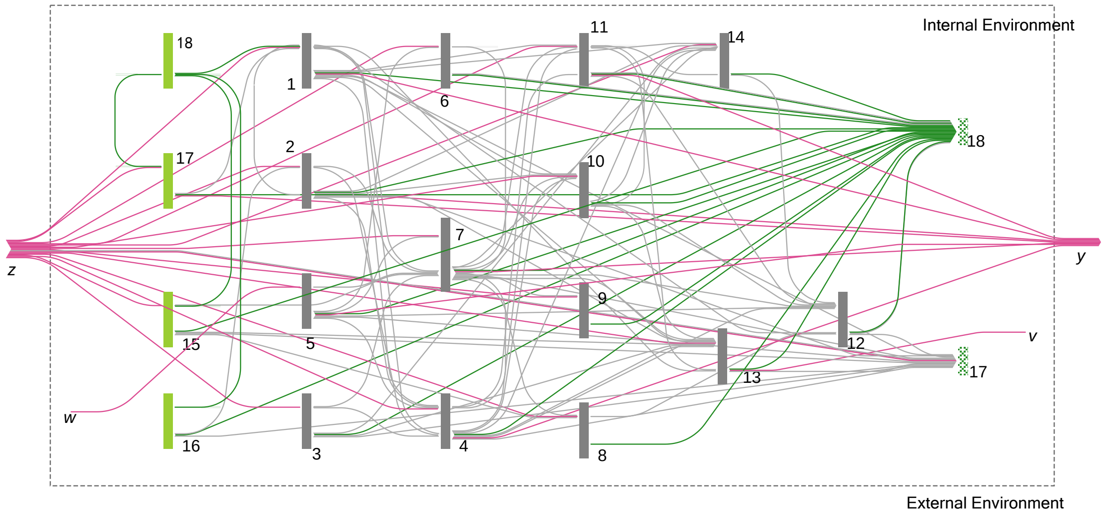


Fig. 1. A schematic diagram of the carbon flows in Beijing's carbon metabolism. Green and grey rectangles represent the natural and socioeconomic metabolic actors, respectively. Actors 17 (water) and 18 (atmosphere) on the right side of the figure map to the corresponding actors on the left side of the figure, but have been repeated to emphasize that all carbon flows in the figure are from left to right. The paths that meet the upper and lower parts of each actor represent the inflow and outflow paths, respectively. Green lines represent sequestration or emission of CO_2. Red lines represent carbon inputs or outputs from or to the internal and external environments, and grey lines represent carbon transmission between actors. Actors: 1, Agriculture; 2, Animal Husbandry; 3, Fisheries; 4, Manufacturing; 5, Mining; 6, Electricity and Heat Production; 7, Energy Conversion; 8, Construction; 9, Transportation; 10, Retail and Catering; 11, Other Services; 12, Waste Disposal; 13, Rural Life; 14, Urban Life; 15, Forest; 16, Grassland; 17, Bodies of Water; 18, Atmosphere. The flows labeled *z* represent inputs for actors derived from the external environment; the flows labeled *y* represent outputs to the external environment from the actors; the flows labeled *w* represent inputs for actors from the internal environment; and the flows labeled *v* represent outputs into the internal environment by the actors.

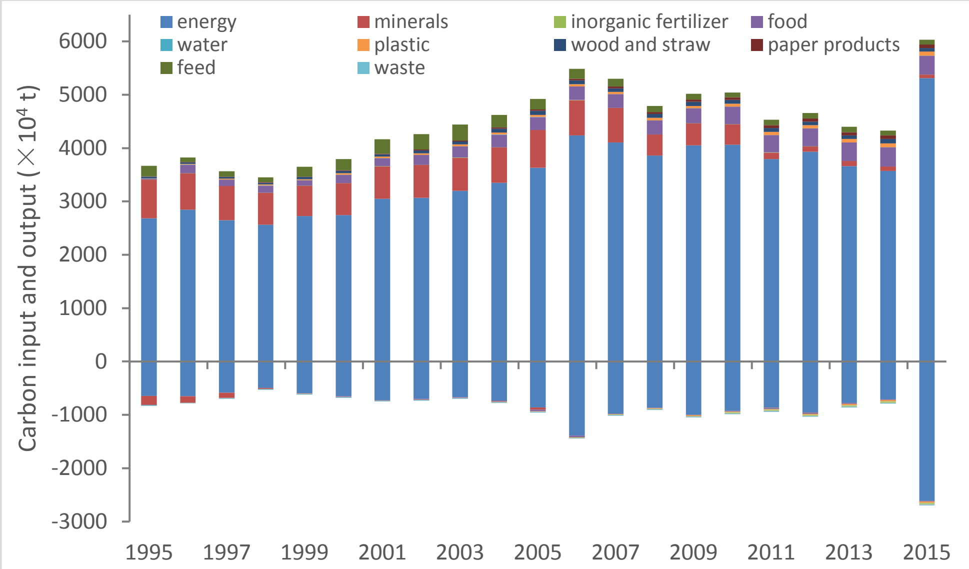


Fig. 2. Total carbon inputs and outputs of Beijing's carbon metabolic system from 1995 to 2015 and the resulting changes in the material structure. Positive values represent carbon in input materials; negative values represent carbon in output materials.

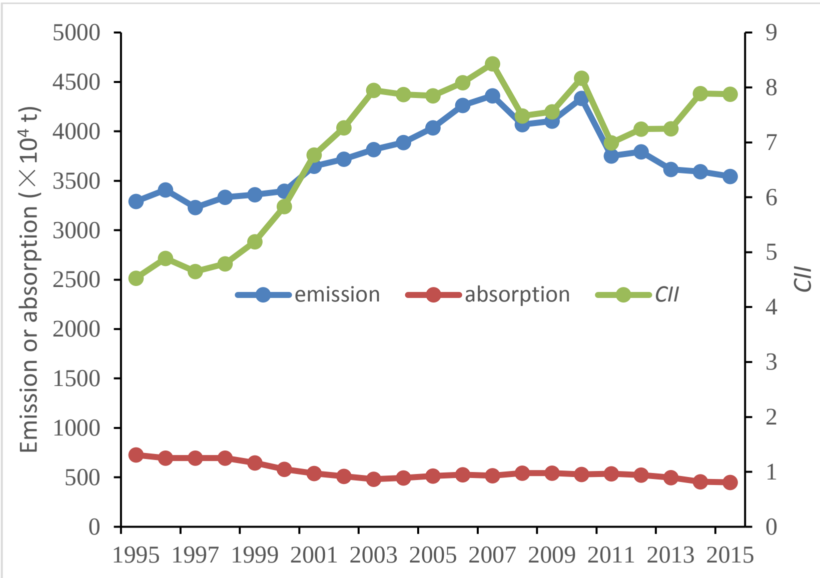


Fig. 3. Changes in the value of the carbon imbalance index (*CII*) for Beijing from 1995 to 2015.

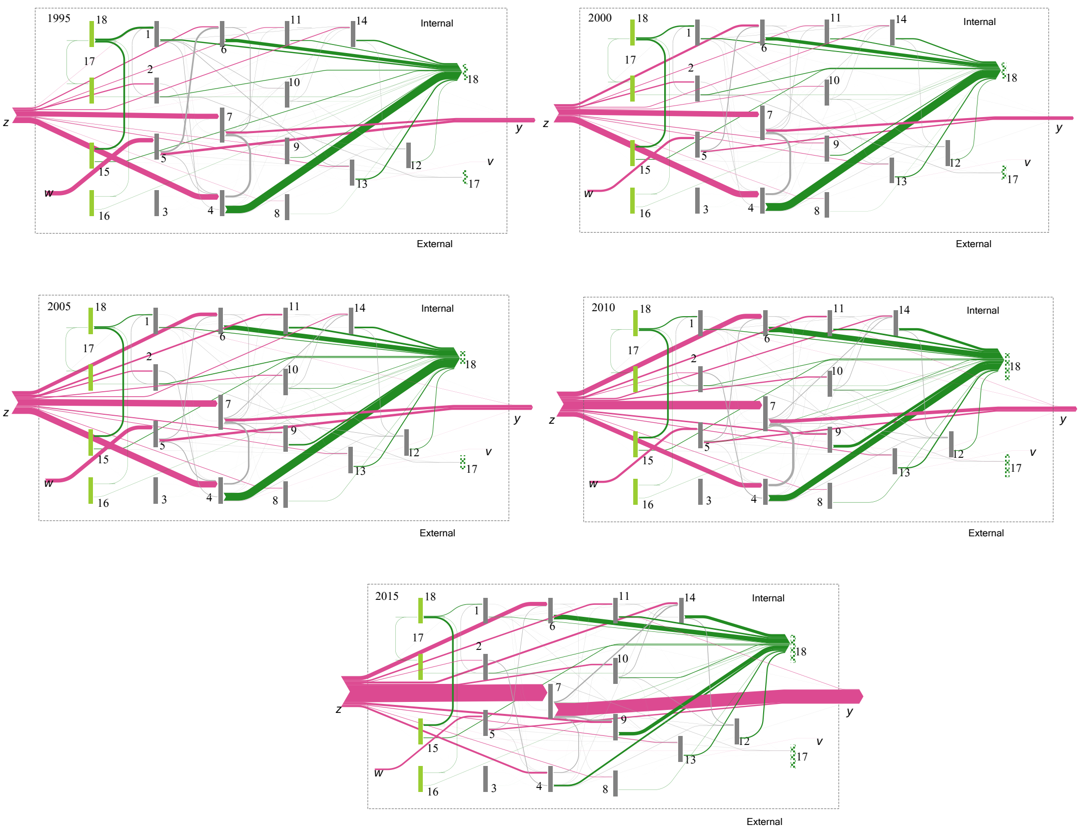


Fig. 4. Carbon flows among the actors in Beijing's carbon metabolic system from 1995 to 2015. The path width represents the size of the flow, and the paths connected to the upper and lower halves of an actor represent the input and output paths, respectively. Green and grey rectangles represent the natural and socioeconomic metabolic actors, respectively. Green lines represent sequestration or emission of CO_2. Red lines represent carbon input or output from or to the internal and external environments, and grey lines represent carbon transmission between actors. Actors: 1, Agriculture; 2, Animal Husbandry; 3, Fisheries; 4, Manufacturing; 5, Mining; 6, Electricity and Heat Production; 7, Energy Conversion; 8, Construction; 9, Transportation; 10, Retail and Catering; 11, Other Services; 12, Waste Disposal; 13, Rural Life; 14, Urban Life; 15, Forest; 16, Grassland; 17, Bodies of Water; 18, Atmosphere.

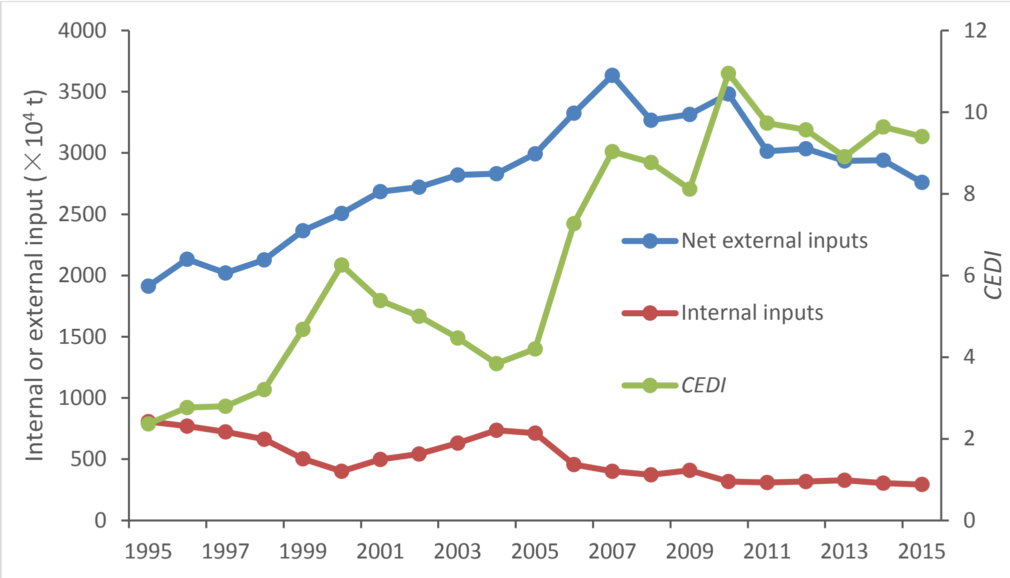
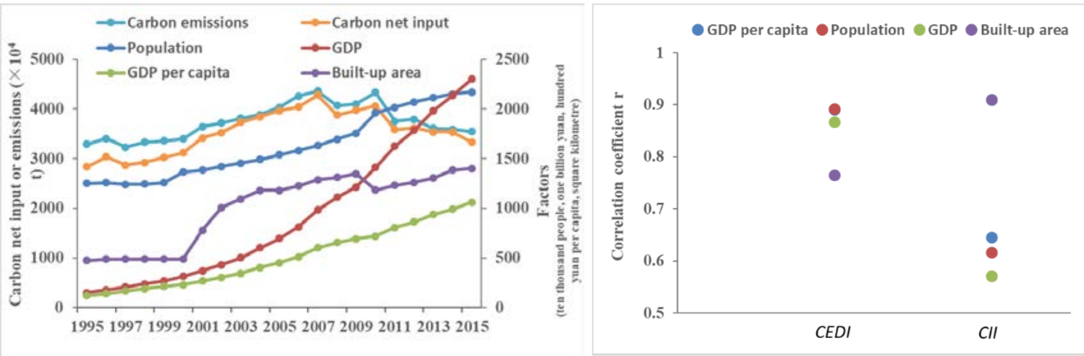


Fig. 5. Changes in the carbon external dependence index (*CEDI*) for Beijing's carbon metabolic system from 1995 to 2015, and contributions of the dependence on internal and external resources to the changes.



(a) The changes of net carbon inputs and emissions in relation to changes in the socioeconomic indicators (GDP, per capita GDP, population, and built-up area) during the study period.

(b) The correlations (Pearson's *r*) between the socioeconomic development indicators and the carbon indicators (*CEDI* and *CII*). The dot of per capita GDP coincides with the dot of population for *CEDI*.

Fig.6.