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Ecological network analysis of an urban metabolic system based on input–output tables: Model development and case study for Beijing

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HIGHLIGHTS

- We used embodied ecological element intensity to build physical input–output tables.
- We developed an ecological network model for Beijing with 32 compartments.
- We studied relationships within the network using ecological network analysis.
- The results defined the ecological hierarchy of the urban metabolic system.

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ABSTRACT

If cities are considered as "superorganisms", then disorders of their metabolic processes cause something analogous to an "urban disease". It is therefore helpful to identify the causes of such disorders by analyzing the inner mechanisms that control urban metabolic processes. Combining input–output analysis with ecological network analysis lets researchers study the functional relationships and hierarchy of the urban metabolic processes, thereby providing direct support for the analysis of urban disease. In this paper, using Beijing as an example, we develop a model of an urban metabolic system that accounts for the intensity of the embodied ecological elements using monetary input–output tables from 1997, 2000, 2002, 2005, and 2007, and use this data to compile the corresponding physical input–output tables. This approach described the various flows of ecological elements through urban metabolic processes and let us build an ecological network model with 32 components. Then, using two methods from ecological network analysis (flow analysis and utility analysis), we quantitatively analyzed the physical input–output relationships among urban components, determined the ecological hierarchy of the components of the metabolic system, and determined the distribution of advantage-dominated and disadvantage-dominated relationships, thereby providing scientific support to guide restructuring of the urban metabolic system in an effort to prevent or cure urban "diseases".

1. Introduction

If a city is considered as a superorganism, then by analogy, "urban disease" can be caused by excessively large metabolic throughput, low metabolic efficiency, and disorders of the city's metabolic processes (Brunner, 2007; Grünbühel et al., 2003; Kennedy et al., 2007). With the recent acceleration of urbanization, particularly in developing countries such as China, attention has focused on the problems of urban metabolism (Kennedy et al., 2007; Lee et al., 2009; Marull et al., 2010; Warren-Rhodes and Koenig, 2001). When Wolman (1965) first proposed the concept of urban metabolism, he regarded the city as analogous to an ecosystem, and proposed that urban metabolism comprised the processes by which materials, energy, and food were imported into the ecosystem while products and wastes were exported from that system.

After Wolman, many scholars have developed a range of interpretations and extensions of the concept of urban metabolism (e.g., Codoban and Kennedy, 2008; Huang and Hsu, 2003; Huang et al., 2006; Kennedy et al., 2007; Warren-Rhodes and Koenig, 2001). The application of urban metabolism has been widely adopted in studies that accounted for and assessed the health of urban systems. This method has been applied to cities in the U.S. (Wolman, 1965), to Hong Kong (Boyden et al., 1981; Newcombe et al., 1978; Warren-Rhodes and Koenig, 2001), to Toronto (Codoban and Kennedy, 2008), to Shenzhen (Yan et al., 2003), and to Taipei (Huang et al., 2006). These studies have mostly focused on the external characteristics of the urban metabolic system, such as the overall inputs and outputs, and few studies have included details of the specific metabolic processes that underlie these overall patterns or have

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simulated the system's structural attributes (Zhang et al., 2009a, 2009b, 2009c, 2010a, 2010b, 2011b). Therefore, it has been difficult to understand the flows of ecological and other elements through the system.

To analyze the flows among the components that make up the sectors of an urban metabolic system, it is reasonable to adopt the input–output approach. In the 1970s and subsequently, the input–output method was applied to calculate the implied resources that flow through the system, such as water (Hite and Laurent, 1971), energy (Herendeen, 1979; Wright, 1974), wastes (Liang and Zhang, 2011), and natural resources (Wright, 1975; Xu, 2010). This method can only analyze the implied ecological elements embodied in flows such as consumer goods, and cannot determine the implied ecological elements of intermediate products. This means that the environmental input and output method can only study the utilization of ecological elements in consumption activities and can only analyze the responsibility of consumers (and not producers) for these flows (Chen, 2011; Chen et al., 2010).

To solve these problems, some scholars have combined the tools of system ecology with economic input–output models to develop equilibrium equations that account for the flows of implied ecological elements. These equations can capture the distribution of implied ecological elements embodied in any product flow, including final consumer goods and intermediate products (Chen, 2011; Chen et al., 2010). However, such studies have mostly focused on key ecological elements such as energy, greenhouse gases, and water, but have not examined the distribution of an urban economy's total input resources among the sectors.

Ecological network analysis is an effective method to study a system's structure and functions, making it possible to analyze the structural distribution and functional relationships within the system. Ecological network analysis developed from the input–output method (Leontief, 1936), and was first proposed by Patten (1978). This method can simulate the flows of materials and energy in an ecosystem from a holistic perspective and can analyze the structure and function of the system (Finn, 1976). In recent years, many studies have used ecological network analysis, but they have mostly concentrated on natural ecosystems. Fewer studies have examined hybrid socioeconomic and ecological systems, and of these studies, most have examined only a single sector, such as an industry (Chen, 2003), fisheries (Pauly et al., 1998; Walters et al., 1997), energy (Zhang et al., 2010b; Zhao, 2006), or water resources (Bodini and Bondavalli, 2002; Li et al., 2009; Zhang et al., 2010a); others have analyzed single elements or products, such as aluminum (Bailey et al., 2004a) and carpeting (Bailey et al., 2004b).

In this paper, we analyzed Chinese statistical data to create monetary input–output tables for Beijing in 1997, 2000, 2002, 2005, and 2007. We then combined this data with an embodied ecological element intensity factor to account for the consumption of ecological elements by urban metabolic processes and compiled corresponding physical input–output tables that accounted for many ecological elements. We concluded our study of Beijing by using flow analysis and utility analysis, two methods from ecological network theory, to analyze the ecological relationships within the hierarchy of Beijing's urban metabolic system. Based on the results of this analysis, we discuss the structure, processes, and function of the metabolic system to provide a scientific basis for promoting healthier development of Beijing's urban ecological system.

2. Defining “urban disease” and an ecological research framework

2.1. Urban disease

Many scholars have discussed the definitions of “urban disease” and of the “health status” of an urban ecosystem from social, economic, and ecological perspectives. In 1988, the World Health Organization proposed that a healthy city is one that is continually creating and improving its physical and social environments so as to expand the community resources that enable people to support each other while they perform all the functions of life and strive to achieve their maximum potential (Hancock and Duhl, 1988). However, this definition mostly focused on social aspects of cities. McMullan (1997) integrated the economic and ecological aspects of cities, noting that a healthy urban system also encompasses the complex interplays among the environment and the social, economic, environmental, and political factors that define a group of people living in an urban area. Subsequently, scholars have attempted to integrate the social and ecological aspects of urban systems. For example, Hancock (2000) proposed that a healthy urban ecosystem must support the population's health and distribution, societal well-being, governmental management, social equity, human habitat quality and convenience, and the quality of the natural environment, and must minimize the urbanization impact on the quality of the larger-scale natural ecosystem that sustains the city and its residents. This complex natural–economic–social urban ecosystem must be stable and sustainable, and must be able to resist adverse external factors so that it can persistently provide ecosystem services for urban residents (Guo, 2003). Some scholars evaluated the principles of ecosystem health from an ecological perspective and described health as homeostasis, as the absence of disease, as diversity or complexity, as stability or resilience, as vigor or scope for growth, and as balance among the system's components (Costanza, 1992). Many subsequent studies have continued this focus and have characterized a healthy urban system as vigorous, having potential to grow, having resilience and the ability to recover from disturbance, having a stable structure, and being capable of maintaining its key functions (Liu et al., 2009; Su et al., 2009, 2010).

Some scholars have also analyzed disruption of these conditions, which they considered to be symptomatic of an “urban disease”, and have treated such diseases as a “syndrome” (Duan, 2001) or a harmful effect (Yu, 2008). An urban disease tends to arise from social and economic development, rather than from the cessation of this development. The most obvious feature of urban disease is that the requirements of the urban population exceed the capacity of the urban ecosystem to meet these requirements as a result of overdevelopment that leads to unsustainable exploitation and utilization of resources (Duan, 2001). Unfortunately, previous studies only analyzed external characteristics such as environmental pollution or resource misuse, and neglected the internal biophysical characteristics of the system. This is an important omission, because an unreasonable or unsustainable structural distribution of resource production and consumption and inappropriate functional relationships among the internal components of the urban system lie at the root of urban disease.

In this study, we have redefined urban disease to account for both external characteristics of an urban system and its internal processes. First, we analyzed the external symptoms of disease, such as urban environmental pollution and declining availability of nonrenewable resources. We then examined the system's internal processes, and explored the internal factors responsible for the “pathogenesis” that creates these external symptoms of disease and the associated metabolic processes. Our internal analysis included a consideration of whether the structural distribution of the city's industries and their role in the overall operation of the system is sustainable and whether their functional relationships are harmonious. This approach overcomes the limitations of only analyzing the external symptoms of disease. It's important to note that a disease results from “pathogenesis”, the process by which an apparently healthy system transforms into a diseased system. This process may take a long time, and a deep analysis is necessary to detect the disease in its early (latent) stages. Analyzing urban disease based only on the system's external characteristics is a limited and inaccurate approach because it cannot detect the latent stages of the disease. Therefore, it is necessary to combine a study of the internal pathogenesis and the external disease symptoms, since this is the only way to detect urban disease in a sufficiently timely manner to permit effective treatment.

2.2. Ecological framework

Analysis of the ecological components of an urban system must be conducted within a framework that includes definition of the subject of the research, the research perspectives, the underlying concepts, and the content of the research, all from an ecological perspective.

First, we must define the subject of the research: the urban system, which can be seen as a large organism—complex (a "superorganism") because of the similarities in features between the urban system and an organism (note, we recognize the diminishing controls up hierarchical scales). These similarities include: (1) Both are independent systems that exchange resources with their environment (for a city, with regions outside the city), and their development occurs within that environment as a result of specific exchange processes. (2) An organism experiences birth, growth, maturation, and death; the urban equivalents are establishment, growth, maturation (leading to prosperity), and possibly death due to depletion of the city's resources. (3) Heritable characteristics that are acted on by selective forces. For an organism, these characteristics are genes. For an urban system, these characteristics are the socioeconomic system that established the urban system and its concomitant infrastructure; the responsiveness to socioeconomic and environmental pressures that cause the city to adapt, innovate, and change the structure, functions, or relationships within the system, and if the changes are successful, the city survives. (4) Both biological organisms and urban systems require a metabolism to survive and to grow, and this metabolism both consumes inputs and generates wastes.

Second, we must define the research perspective, which is based on the analogy between biological metabolism and urban metabolic processes. A city's processes simulate the cycling mechanisms of a natural ecosystem, and using the insights that have been gained from studying organisms and natural ecosystems helps us to better understand the metabolic processes that underlie an urban system (Zhang, 2013). The overall urban metabolic processes start with the intake of raw materials (e.g., nutrients in an organic system) from the external environment followed by the consumption of these resources by the system's social and economic components to permit the system's operation, accompanied by the production of wastes. These wastes are metabolites that must be either disposed of or treated and reused. Within these processes, heritability and responses to external selection pressure are also important. Although urban systems lack genes, they nonetheless inherit infrastructure as well as rules and processes that governed the urban development. City managers must modify these processes in response to external pressures such as new guidelines that constrain pollutant emission, a lack of certain resources in the external environment, and market pressures. Changes in these legal and management codes are analogous to mutations, and if the change permits the survival of the urban system, the changes are retained in much the same way that beneficial genetic mutations are retained. An urban system can also adopt innovations from other systems or have its innovations adopted by other urban systems. The overall set of processes, including inputs, transfers, outputs, and reuptake by the system, work together to develop a stable system. When the urban system does not produce unsustainable impacts on its support systems, this can represent a harmonious situation. However, one or more processes can create problems with the urban ecological environment. In this case, urban managers must seek to imitate the more efficient cycling mechanisms of an organism or ecosystem, and analyzing the urban metabolic processes can reveal the nature of the problems and suggest possible solutions. To increase the likelihood of healthy development of the urban organism, we must try to diagnose metabolic diseases, analyze the underlying pathogenesis, and propose a cure.

Third, we must define the basic concepts. An ecological network is a representation of the biotic interactions in an ecosystem, in which species (nodes) are connected by pairwise interactions (links). These interactions can be trophic (e.g., primary consumers that consume primary producers) or relational (e.g., competition versus mutualism). These interactions also exist between the components of an urban metabolic system. The components and the exchanges between them can be represented as a collection of flows, and the exchanges of materials and energy through pairwise interactions resemble those in an ecological network (Fath and Patten, 1998). Therefore, the concept of an ecological network and the associated analytical approaches are also suitable for analyzing an urban metabolic system. The relationships between components can be compared to the ecological interactions between species in a natural system, and any flaws in these interactions can reveal the pathogenesis that leads to an urban disease. The techniques of ecological network analysis can effectively analyze the sustainability and existence of harmonious relationships in the urban system and can diagnose urban disease. For example, Mageau et al. (1998), Ho and Ulanowicz (2005), and Ulanowicz et al. (2009) chose system-level indices such as resilience and various efficiencies to quantitatively analyze the sustainability of an urban system. Bodini and Bondavalli (2002) and Bodini (2012) applied some of these concepts in an urban context to examine the urban water system and to expand the meaning of sustainability. Zhang et al. (2010a, 2010b, 2011a, 2012a, 2012b) and Li et al. (2012) quantitatively studied the paths and structures of different socioeconomic systems, and described the ecological flows and the resulting ecological relationships between components of the system. This approach reveals diseases and their pathogenesis, but also makes the ecological connotations of the underlying processes clear.

Finally, the urban system can be assessed in terms of its symbioses, health, and sustainability. One approach is network synergism (Patten, 1991, 1992), which uses utility analysis to normalize the values of the net flow between pairs of components, and to calculate both direct utilities of these flows and their integral values. The results can then be compared, with positive and negative net flows representing benefits and costs, respectively (Fath and Patten, 1998). The ecological relationships revealed by this utility analysis can reveal the nature of the relationships between any two components of the system, which can then be classified into mutualism, competition, control, exploitation, and neutral relationships. The system's overall sustainability (Ho and Ulanowicz, 2005; Mageau et al., 1998; Ulanowicz et al., 2009) can be assessed using system-level indicators that can be used to quantify the system's resilience, efficiency and sustainability. However, this sustainability results from the net effects of the system's internal processes, and these can be examined in more detail by analyzing the distribution of the trophic levels and functional relationships among the components of the system. In trophic level analysis (Ulanowicz and Kemp, 1979; Ulanowicz and Puccia 1990), most complicated webs of exchanges can be transformed into a simpler representation that resembles the trophic pyramid of a typical ecological system and the mixture of trophic levels and relational interactions between the system's components can then be understood more intuitively.

Fig. 1 illustrates the ecological framework that results from the consideration of the abovementioned factors and which we used to guide our research.

3. Methods and data used

3.1. Compiling the physical input–output table

We used input–output analysis for our study because it is an effective approach to quantitatively analyze the input and output relationships between pairs of industrial components. In this study, economic data were available for all key flows, whereas physical flow data were not; thus, we began our analysis with economic data on the flows between components as a result of metabolic processes, and we converted these monetary input and output value flows into material and energy flows using appropriate conversion factors. This let us quantify urban metabolic processes for which no material or energy data were available and provide a more complete description of the system. The results also let us describe the structural distribution and functional relationships within the urban system. Although input–output analysis cannot directly reveal urban disease, it can provide a basis for identifying and analyzing the problematic processes that may lead to urban disease.

To convert the economic data into physical data, we used an embodied ecological element intensity factor that let us transform the monetary

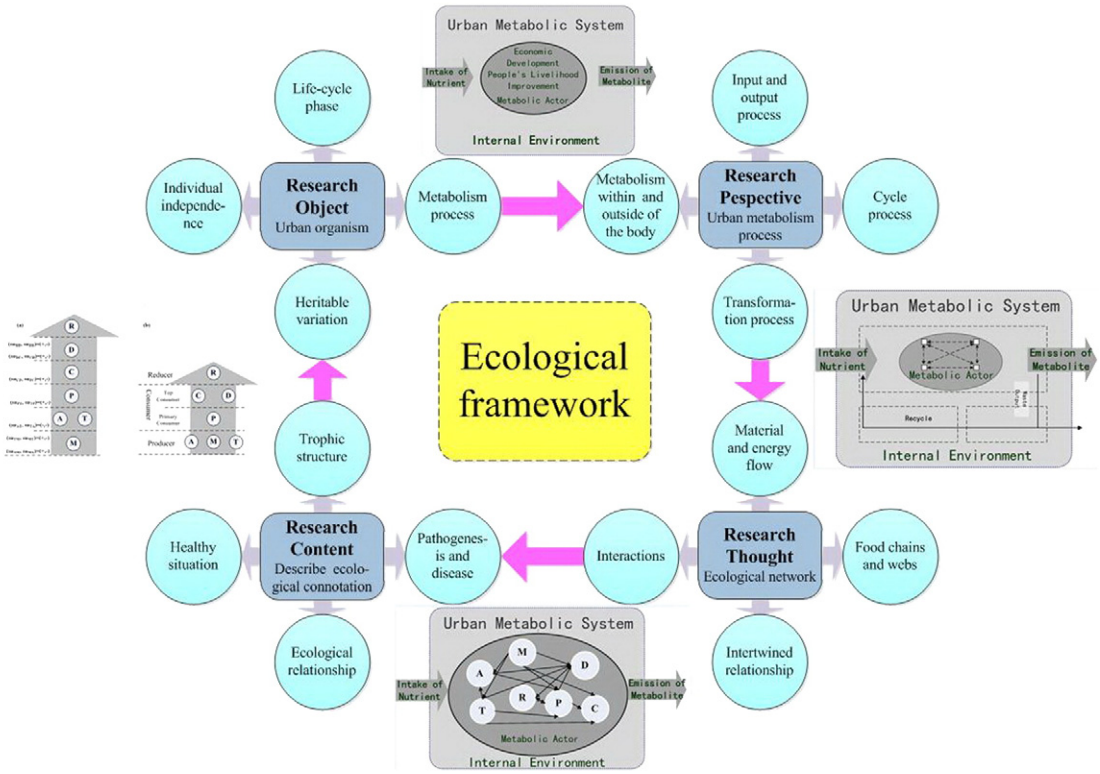


Fig. 1. The ecological framework for the ecological connotations. A, agriculture; C, construction; D, domestic consumption; M, mining; P, processing and manufacturing; R, recycling; T, materials and energy transformation.

input–output tables into physical input–output tables. This factor represents the quantity of an ecological element per unit of monetary value embodied in the exchanges of that element within the system, which allows us to estimate the intensity of the consumption of ecological elements by each sector or component of the system (Chen, 2011).

In addition to consuming ecological elements directly, the sectors and components of the urban metabolic processes also utilize ecological elements indirectly during the production and consumption of intermediate products. We obtained the implied overall flow of ecological elements embodied in the creation, transport, and recycling or reuse of a specific product throughout its lifetime within the system (Lenzen, 1998; Reinders et al., 2003). The ecological elements that are consumed to sustain the system's operation should include consumption of both the initial ecological elements (e.g., raw materials) and the implied ecological elements. The implied ecological elements can be determined by multiplying the embodied ecological element intensity factor (i.e., the value per unit of flow) by the corresponding economic flow, thereby generating the physical input–output tables.

First, we developed an input matrix for the initial ecological elements that will serve as primary elements of the monetary input–output tables. Next, we constructed input–output tables that combined both monetary and physical flows for these inputs, which form the basis for all subsequent flows among sectors and components. The order of the economic input–output tables for each year in our study period is $n \times n$, where n represents the number of sectors in the system. The order of the input matrix for the ecological elements is $(m + s) \times n$, where m represents the number of types of ecological elements and s represents the number of types of wastes. The structure of the initial tables does not change, but the input–output tables can then be divided into a value module (which comprises monetary flows) and a physical module (which comprises flows of ecological elements). From this data, we can construct physical–monetary input–output tables that capture the socioeconomic and environmental flows (Table 1). The value of the flows into and out of sector i and the specific process are described in Fig. 2, and based on these flows, we can establish the ecological element equation for sector i. In addition to the direct ecological elements consumed by sector i, the sector also indirectly consumes ecological elements embodied in intermediate products received from other sectors. Therefore, when a sector exchanges a value flow with other sectors, these value flows embody ecological element flows.

We used the concept of an embodied ecological element intensity to convert the monetary input–output table into a physical input–output table. The derivation of the embodied ecological element intensity matrix is described in Appendix A. The embodied ecological element intensity matrix $\boldsymbol{\varepsilon}\mathbf{U}$ is:

$$\mathbf{P} + \boldsymbol{\varepsilon}\mathbf{H} = \boldsymbol{\varepsilon}\mathbf{U} \tag{1}$$

where $\mathbf{P}$ represents the resource and waste that enter or flow out matrix, $\boldsymbol{\varepsilon}$ represents the embodied ecological intensity matrix, and $\mathbf{H}$ represents the value flow matrix. Then:

$$\varepsilon = \mathbf{P}[\mathbf{U}-\mathbf{H}]^{-1} \tag{2}$$

where $\mathbf{H} = [h_{ij}]_{n \times n}$, $h_{ji} = x_{ji}$, $\mathbf{P} = [p_{ki} \ \ r_{ki}]_{(m+s) \times n}$, and $\varepsilon = [\varepsilon_{ki}]_{m \times n}$. Here, the definitions for the parameters are defined in Table 1. If k represents an ecological element whose consumption intensity is embodied in the products of sector i, then ε_{ki} represents the consumption intensity of the k-th ecological element embodied in the products produced by sector i. $\mathbf{U} = [u_{ji}]_{n \times n}$ when $i = j$ and $u_{ji} = X_i$, where X_i is the economic output of sector i, and is calculated using Eq. (2) in Appendix A; and when $i \neq j$, $u_{ji} = 0$ for an urban metabolic system that includes n sectors and $m + s$ types of ecological elements.

In this study, we analyzed the urban metabolism of Beijing in 1997, 2000, 2002, 2005, and 2007, and developed physical input–output tables for each year. In the monetary input–output table established by the government, the 42 components form a 42×42 matrix of flows between pairs of components. We combined these

Table 1
The basic form of the monetary–physical input–output table.

Input \ Output		Sector				Final use					
		1	2	…	n	Consumption	Capital formation	Transfer-in	Imports	Transfer-out	Exports
Sector	1	x_{11}	x_{12}	…	x_{1n}	q_{1L}	q_{1C}	d_{E1}	d_{M1}	q_{1E}	q_{1M}
	2	x_{21}	x_{22}	…	x_{2n}	q_{2L}	q_{2C}	d_{E2}	d_{M2}	q_{2E}	q_{2M}
	…	…	…	…	…	…	…	…	…	…	…
	n	xn_1	xn_2	…	x_{nn}	q_{nL}	q_{nC}	d_{En}	d_{Mn}	q_{nE}	q_{nM}
Non-industrial input		w_1	w_2	…	w_n						
The initial resource inputs	Category 1	p_{11}	p_{12}	…	p_{1n}						
	Category 2	p_{21}	p_{22}	…	p_{2n}						
	……	…	…	…	…						
	Category m	p_{m1}	p_{m2}	…	p_{mn}						
The waste emissions	Category m+1	$r_{(m+1)1}$	$r_{(m+1)2}$		$r_{(m+1)n}$						
	Category m+2	$r_{(m+2)1}$	$r_{(m+2)2}$		$r_{(m+2)n}$						
	……	…	…		…						
	Category m+s	$r_{(m+s)1}$	$r_{(m+s)2}$		$r_{(m+s)n}$						

Sector i

Note: x_{ji} represents the value flows from sector j to sector i; x_{ij} represents value flows from sector i to sector j; d_{Ei} represents the value flow from the external environment (parts of China outside the system being studied) into sector i; q_{iE} represents the value flowing from sector i to the external environment; d_{Mi} represents the value flow into sector i from sectors outside of China; q_{iM} represents the value flow from sector i to sectors outside of China; q_{iL} represents the final consumption value flow for sector i within the system itself; q_{iC} represents the total capital formation in the system itself; and w_i represents the non-industrial input value flow of labor and government services into sector i; p_{ki} represents the m-th flow of resource elements into sector i; r_{ki} represents the k-th waste emitted by sector i, and because wastes (r_{ki}) are inputs, the value should be less than 0.

components into a smaller group of 32 components, including the domestic consumption sector, based on the similarity of their products and the unity of their time series in the physical input–output tables (Supplementary Table S1). The data used for the ecological elements was mainly obtained from the *Beijing Statistical Yearbook*, *Beijing Water Resources Bulletin*, and the *China Mining Statistical Yearbook* from 1998 to 2008 as well as from some other references (Zhang et al., 2012b).

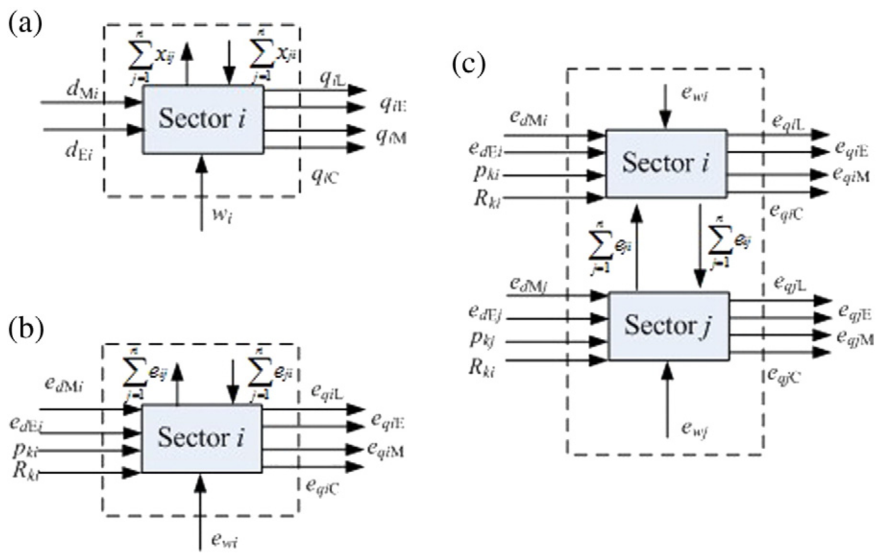


Fig. 2. The accounting relationships for the flow values and energy flows among the sectors. Note: The ecological elements embodied in the value flows are e_{ji} for x_{ji}, e_{ij} for x_{ij}, e_{dEi} for d_{Ei}, e_{dMi} for d_{Mi}, e_{qiL} for q_{iL}, e_{qiC} for q_{iC}, e_{qiE} for q_{iE}, e_{qiM} for q_{iM}, and e_{wi} for w_i. The w_i parameter in the input–output diagram is an added value that represents a weight used to adjust p_{ki}, which represents the value of the initial ecological element input into the system, so that the implied ecological element e_{wi} of w_i equals 0 (Duchin, 2008).

The physical input–output tables include two parts: a monetary intermediate input–output table that accounts for the flows according to the traditional method used for input–output tables, and an ecological input table. Here, “resources” refer to the initial input resources for a sector, indicating the ecological elements obtained from the natural ecosystem. In our analysis, we accounted for four resource types: biological resources (e.g., crops, plants, and farming), energy (mining), non-energy minerals (metals and non-metals), and water. Based on the availability of statistical data for Beijing, we divided these four types into 20 specific materials. We also defined six types of wastes: wastewater, sulfur dioxide, smoke, dust, solid wastes, and carbon dioxide.

Next, we chose the data from 1997 for an example and used that data to provide a detailed example of how to use the ecological element intensity factor to transform the monetary tables into physical input–output tables and create the final flow matrix. We started with the monetary input–output table for 31 components in 1997 (Supplementary Table S2, the green part). At this stage of our analysis, we are focusing on industrial sectors, so we have not included the domestic sector in our analysis. We will add that sector in Section 3.2 when we use the input–output tables to construct our urban network model. We added a new column on the right to contain the total economic output (Supplementary Table S2, the purple part, in which we only list the first five components in detail). The economic output is calculated using the following equation: output = use + total consumption + fixed capital formation + inventory building + exports and outputs − imports and inputs.

These economic output flows (the purple part in Supplementary Table S2) are the elements of the leading diagonal of matrix **U**, and the other elements in this matrix all equal 0. The result is a 31 × 31 matrix. The elements of matrix **H** represent the initial use of each component, and **H** is also a 31 × 31 matrix (the green part in Supplementary Table S2). The matrix (**U**–**H**) is also a 31 × 31 matrix, and it contains the initial monetary values.

By adding the 26 types of resource inputs and waste emissions that are summarized in the government statistics to the monetary input–output table, we can establish a monetary–physical input–output table (Supplementary Table S2). The elements of matrix **P** represent the flows of resource elements into sector *i* and waste emissions by sector *i*. In 1997, the result was a 26 × 31 matrix (the blue part in Supplementary Table S2).

ε represents the embodied ecological element intensity matrix for the sectors, and it is a 26 × 31 matrix. We can then add a final row to the table to include the sum of the values in each column (Supplementary Table S3).

If the transformed value flow can be determined for each sector, then we can multiply the embodied ecological element intensity factor for that sector by the associated flow to compute the quantity of the implied ecological elements in the value flow. Based on these calculations, we can establish a physical input–output matrix that reflects the utilization of the flows of ecological elements between sectors.

We can then establish the final physical input–output table. To do so, we multiply the value flows in a given row (e.g., for agriculture) of the green part of Supplementary Table S2 by the sum of the embodied ecological element intensities for the corresponding component in Supplementary Table S3, respectively. The resulting 31 × 31 matrix is shown in Supplementary Table S4. Because the units of measurement differed among the various flows, we converted all the raw data into units of metric tons (t) to permit direct comparisons of the flows.

3.2. Development of the urban metabolic network model

In the physical input–output tables, we divided the urban metabolism into 31 industrial components, one consumption component (the domestic sector). Beijing's urban metabolic system represents a complex socioeconomic system composed of both industrial (production) components and a consumption component. The environment includes both the natural environment within the city's administrative boundary (which includes a large area of countryside surrounding the built-up urban core) and the economic entities and the natural environment that lie outside the administrative boundary. The environment clearly provides the support required by the socioeconomic system, so when we study the urban metabolic system, we must also consider the inputs from and outputs to the environment (Fig. 3), not just the exchanges of materials and energy among the industrial sectors within the system and between the industrial sectors and the consumption sector.

The only consumption sector included in our model is domestic consumption (which, for the sake of simplicity, we assume includes government consumption). This represents the final consumption component in the physical input–output table. Based on our division of the system's components and the relationships among the components in

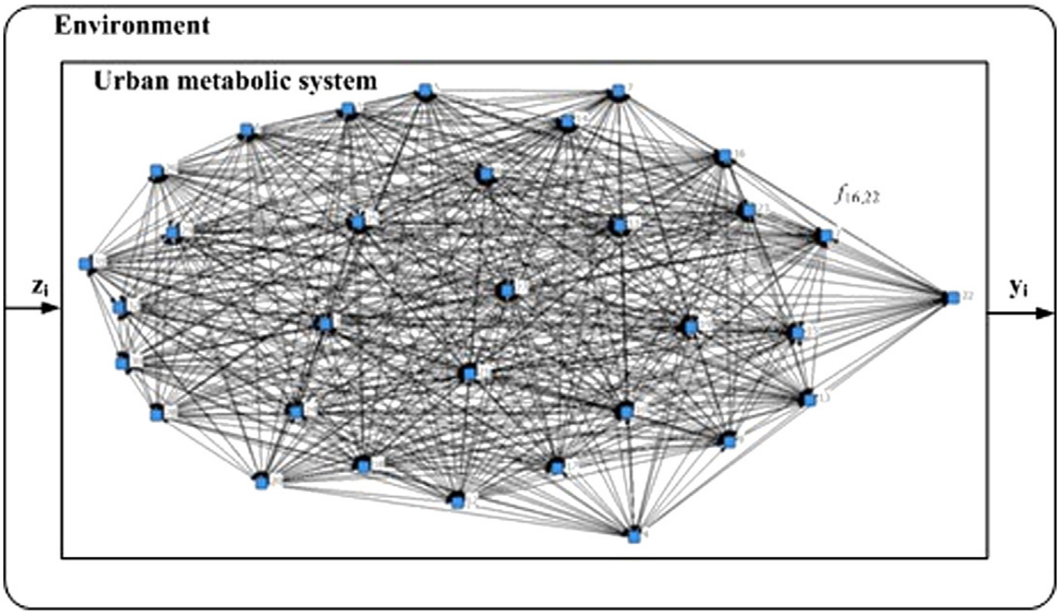


Fig. 3. Network model of the urban metabolic system. For flow *i*, z_i represents inputs from the environment into the system and y_i represents outputs from the system into the environment.

the physical input–output table, we defined the urban metabolic network model shown in Fig. 3. In this model, nodes represent the different components, and directional lines between two nodes represent the exchanges of materials between the nodes. The components in each pair of nodes are represented by i and j, and f_{ji} represents the flow from i to j. Using the input–output method, we can define the inputs and outputs for the exchanges with the environment and the exchanges of ecological elements among the system's components.

In the next part of our analysis, we use an analogy with the trophic levels in a food web or food chain in a natural ecosystem. Based on this analogy, we used a bottom-up method to combine the components of the urban metabolic system into groups at the same trophic level (i.e., producers, consumers, and reducers). This division provides the basis for defining the functions of the components and their positions in the ecological hierarchy. In an urban metabolic system, the producers are components that can utilize basic elements (raw materials such as water and minerals) from the natural environment to produce primary products. These producer components include agriculture (component 1 in Supplementary Table S1) and mining (components 2 to 4). In contrast, consumers are components that can utilize primary products to produce advanced products. These include primary manufacturing (components 5 to 9), advanced manufacturing (components 10 to 20), and materials and energy transformation (components 21 to 23). Consumers also include components that directly consume terminal products (e.g., component 32), tertiary industries that do not produce products but that instead utilize the products produced by producers (components 25 to 31), and the construction sector, which transforms resources into capital stock (component 24). Based on this description, we divided the 32 components into eight sectors (Supplementary Table S1): agriculture, mining, primary manufacturing, advanced manufacturing, materials and energy transformation, construction, tertiary industry, and domestic consumption.

3.3. Ecological network analysis of the urban metabolic system

Ecological network analysis (Fath and Borrett, 2006) can be used to study the ecological relationships between components and the resulting hierarchy. According to the direct flow f_{ij} between pairs of nodes, a dimensionless integral flow intensity matrix ($\mathbf{N}'$) can be computed:

$$\mathbf{N}' = \left(n'_{ij}\right) = (\mathbf{G}')^0 + (\mathbf{G}')^1 + (\mathbf{G}')^2 + (\mathbf{G}')^m + \ldots = (\mathbf{I}\text{–}\mathbf{G}')^{-1} \quad (3)$$

where $\mathbf{G}'$ represents a matrix of flows of a given path length, and the superscript following $\mathbf{G}'$ (which ranges from 0 to k) represents the path length. $\mathbf{I}$ represents the identity matrix. The elements of $\mathbf{G}'$ are:

$$g'_{ij} = f_{ij}/Ti \quad (4)$$

where g'_{ij} represents nondimensional, input-oriented intercomponent flows from component j to component I, and T_i is the sum of the intercomponent and boundary inflows into component i. Because limited data are available for some output flows, and because we have assumed that at equilibrium, inputs must equal outputs for a system, we used the total input flows for i to replace the output flows:

$$T_i = \sum_{j=1}^{n} f_{ij} + z_i. \quad (5)$$

By premultiplying the integral flow intensity matrix by the diagonal of the flow matrix, diag($\mathbf{T}$), we obtain the column matrix $\mathbf{Y}$, which represents the contribution weight of each component (Fath and Patten, 1998; Patten, 1990).

$$\mathbf{Y} = \mathrm{diag}(\mathbf{T})\mathbf{N}' \quad (6)$$

The sum of the columns of matrix $\mathbf{Y}$ equals the row vector of matrix $\mathbf{Y}$, $\mathbf{y}_i = (y_{i1}, y_{i2}, \ldots, y_{i32})$, which reflects the integral flow intensity that other components contribute to $W_i = \sum_{j=1}^{n} y_{ij}/\sum_{i=1}^{n}\sum_{j=1}^{n} y_{ij}$ component i, and $\sum_{j=1}^{n} y_{ij}$ represents the integral flow intensity that the whole system contributes to component i. We can then compute the relative contribution weight (W_i), which reflects the ability of component i to receive ecological elements from other components. W_i represents the component's "pull" on the other components through forward linkages (demand linkages), and is therefore called the "pull force weight" or the "pull force factor", which represents the degree of demand and dependence of this component on the system:

$$W_i = \sum_{j=1}^{n} y_{ij}/\sum_{i=1}^{n}\sum_{j=1}^{n} y_{ij}. \quad (7)$$

In addition, the column vector $\mathbf{y}_j = (y_{1j}, y_{2j}, \ldots, y_{nj})$ represents the integral flow intensity that component j contributes to the other components. $\sum_{i=1}^{n} y_{ij}$ indicates the integral flow intensity that component j contributes to the system. This relative contribution rate reflects the component's ability to deliver ecological elements to other components. This represents the component's ability to drive other components through backward linkages (supply linkages), and is called the "driving force weight" or "driving force factor". It therefore represents the component's degree of importance to the other components in the system:

$$W_j = \sum_{i=1}^{n} y_{ij}/\sum_{i=1}^{n}\sum_{j=1}^{n} y_{ij}. \quad (8)$$

Using W_j, we can compute the influence of each component and its ability to induce changes in downstream components. By combining the upstream and downstream relationships described in this section, we can obtain the ecological hierarchy of the urban metabolic system, and use it to analyze the time series for the system's hierarchy.

Through the elements d_{ij} in the direct utility intensity matrix ($\mathbf{D}$), which is composed of the net flows between components i and j, we can compute the dimensionless integral utility intensity matrix $\mathbf{U}$ (Patten, 1991, 1992):

$$d_{ij} = \left(f_{ij}\text{–}f_{ji}\right)/T_i. \quad (9)$$

In this form of analysis, it is necessary to confirm that the $\mathbf{D}$ matrix converges (Fath and Patten, 1998). We confirmed that the matrix converged before continuing with our analysis. $\mathbf{U}$ then equals the sum of the $\mathbf{D}$ matrices, as follows:

$$\mathbf{U} = \left(u_{ij}\right) = \mathbf{D}^0 + \mathbf{D}^1 + \mathbf{D}^2 + \mathbf{D}^3 + \ldots + \mathbf{D}^k + \ldots = (\mathbf{I}-\mathbf{D})^{-1} \quad (10)$$

where $\mathbf{D}$ represents a matrix of flows of a given path length, and the superscript following $\mathbf{D}$ (which ranges from 0 to k) represents the path length.

Using the positive and negative signs of the elements in the integral utility matrix, we can judge the nature of the relationship between pairs of components. Our analysis only revealed five types of relationships: exploitation (+,−), in which one component receives more benefits than it transfers to the other component; control (−,+), in which one component's outputs are controlled by the other component; competition (−,−), in which both components are harmed by the relationship; neutralism (0,0), in which there is no net effect on either component; and mutualism (+,+), in which both components benefit from the relationship. Because control and exploitation are reciprocal relationships (i.e., they differ only in the direction of the utility flow), we have

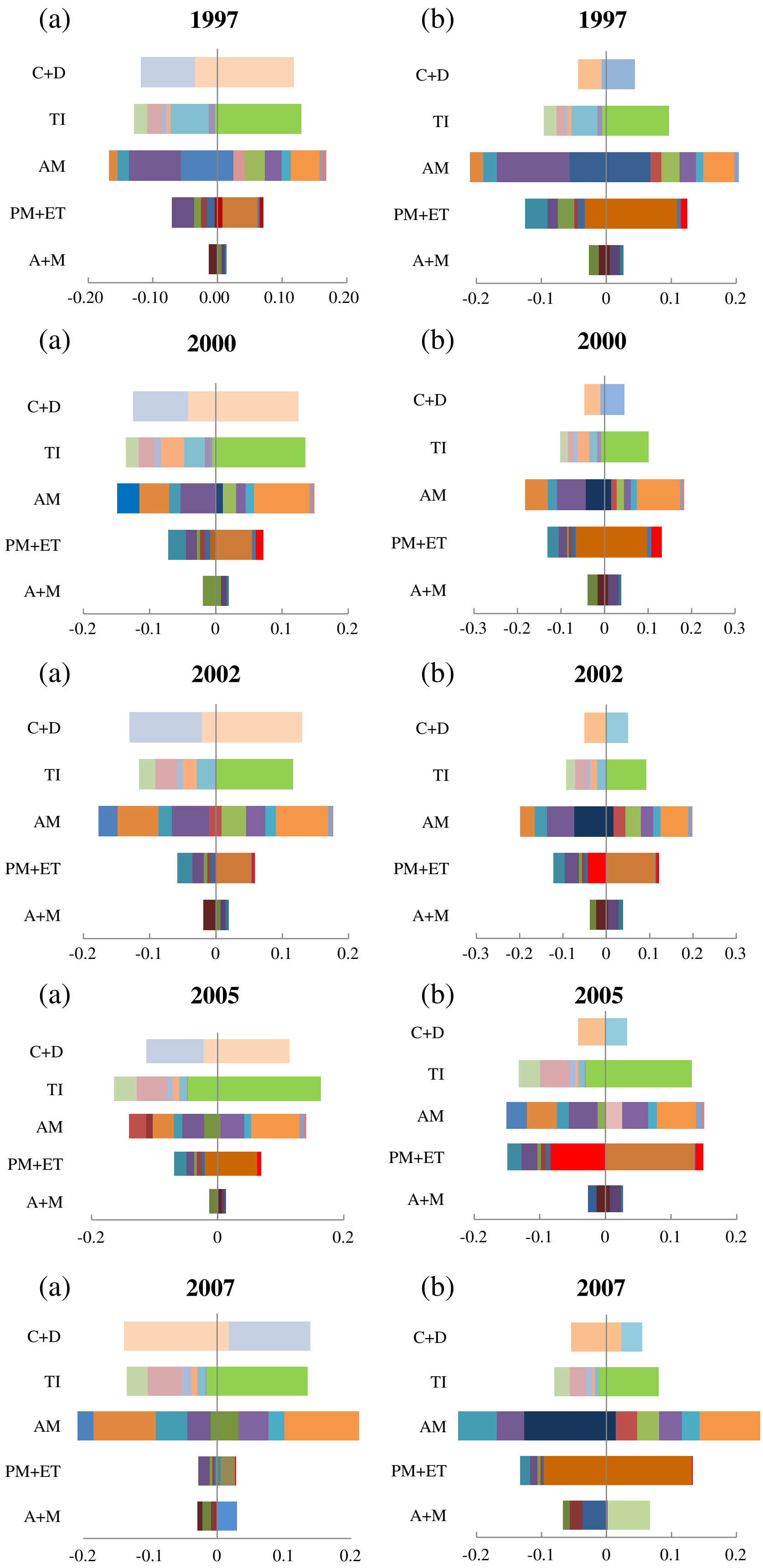


Fig. 4. The ecological hierarchy of (a) the pull weights and (b) the driving weights. A, agriculture; AM, advanced manufacturing; C, construction; D, domestic consumption; E, exploitation; ET, materials and energy transformation; PM, primary manufacturing; TI, tertiary industry.

combined them into a single category in the rest of our analysis, leaving only four relationships. Determining which of these situations describes the relationship between two components provides important insights into the distribution of relationship types within the overall system.

4. Results and discussion

We produced flow matrices for the exchanges of inputs and outputs among the components of Beijing's urban metabolic system, and used the results as inputs for the ecological network analysis. Supplementary Table S5 summarizes the pull and driving weights.

4.1. The ecological hierarchy of the sectors

4.1.1. The ecological hierarchy of the pull weight

Fig. 4a shows that the ecological hierarchy of the pull weight represents an irregular inverted pyramid in all years, which reflects the significant pull function of upstream components on the downstream components. Because China's economic development goal is to increase final consumption and decrease the investment in manufacturing industries to grow the economy, the inverted pyramid structure is a suitable state, since it indicates that consumers at upper levels of the hierarchy accounted for a large proportion of the flows and can therefore promote the development of the downstream industries, including basic and manufacturing industries. The main reasons for the irregular inverted pyramid structure are that the construction and domestic consumption sectors pulled their downstream components insufficiently, whereas the advanced manufacturing and tertiary industry sectors pulled other sectors too fast. Specifically, the tertiary industry sector pulled excessively and the construction and domestic sectors pulled insufficiently in 1997, 2000, and 2005. The advanced manufacturing sector pulled too hard in 2000, 2002, and 2007. These results highlight China's economic development pattern, which is dominated by production industries and supplemented by domestic consumption.

The pull weight of the agriculture and mining sectors was greatly insufficient, with all weights less than 5% during the study period. The pull weights of the primary manufacturing sector and the materials and energy transformation sector decreased gradually, from 14.1% in 1997 to 5.5% in 2007. In contrast, the pull weight of the advanced manufacturing sector increased from 33.6% in 1997 to 45.9% in 2007, which reflects the fact that Beijing's development focus has changed from primary processing to deep processing of primary products and the fact that Beijing has aggressively developed its high-tech and high-added-value industries. The pull weight of tertiary industry fluctuated and the overall trend was not obvious, suggesting that the development of Beijing's tertiary industry sector has been unstable. The changes in the pull weight of the construction and domestic sectors were not significant; their development and their ability to pull economic development are both inadequate, suggesting that Beijing's economic development pattern is not yet dominated by services and consumption.

The primary manufacturing sector and the materials and energy transformation sector shrank from 1997 to 2007 because the pull weight of component 6 (textile manufacturing) decreased to 6.9% of the total pull weight for the primary manufacturing sector, from 15.1% of the pull weight in 1997, and the pull weight of component 23 (production and distribution of water) decreased to 8.4% of the total, from 4.3% in 1997. The pull weight of the advanced manufacturing sector increased mainly as a result of increases in two components: 12 (manufacturing of non-metallic mineral products) and 13 (smelting and pressing of metals). Their pull weights increased to 10.2 and 20.3% of the total for this sector, respectively. In addition, the pull weights of components 16 (manufacturing of transportation equipment), 18 (manufacturing of communication equipment, computers, and other electronic equipment), and 19 (manufacturing of measuring instruments and machinery for cultural activities and office work) increased to 9.9, 24.2, and 1.8%, respectively, of the total for this sector in 2007. The pull weight of the tertiary industry sector varied among the components. The pull weights of components 26 (postal services) and 27 (financial industry) declined obviously, especially for the financial industry (to 4.7% of the total for this sector). In contrast, component 30 (integrated technical services) grew to 19.1% of the total for the sector, from 8.8% in 1997. Based on these results, Beijing should adjust its industrial structure to simultaneously modify the components with decreased pull weight and better develop the components with increased pull weight.

4.1.2. The ecological hierarchy of the driving weights

Fig. 4b shows that the driving weights of the agriculture and mining sectors were both small, with less than 12% of the total driving weight in the ecological hierarchy. This reflects the fact that Beijing's agricultural and mining product sectors depend strongly on supplies from the external environment and the fact that production by these components lags far behind the demand for their products. This situation relates to Beijing's natural resource endowments, and the fact that as China's capital, the population and economic activity are both highly concentrated, leading to a seriously inadequate agricultural capacity within the system. If we exclude the insufficient driving weights of the agriculture and mining sectors, the ecological hierarchy shows an irregular pyramid structure overall. This structure shows how escalating industrial development leads to a progressively increasing driving weight from basic industry to primary manufacturing, advanced manufacturing, and the domestic sector. Thus, the pyramid structure represents a good state of development and indicates that the underlying suppliers promote and support the upper-level consumers. The irregular pyramid structure mainly resulted from the too-large or too-small driving weights of the advanced manufacturing, primary manufacturing, and materials and energy transformation sectors. Specifically, the driving weight of the advanced manufacturing sector was inadequate in 2005. The driving weights of the primary manufacturing sector and the materials and energy transformation sector were insufficient in 1997, 2000, 2002, and 2007, whereas the driving weight of the advanced manufacturing sector was too strong.

The driving weights of the primary manufacturing and the materials and energy transformation sector were lower than that of the advanced manufacturing sector in the 5 years, ranging from 25 to 30% of the total. The driving weight of the advanced manufacturing sector increased from 41.8% in 1997 to 51.1% in 2007, which was much more powerful than its pull weight (which increased from 33.6% in 1997 to 45.9% in 2007), indicating its basic support role for Beijing's economy. The driving weight of tertiary industry changed unstably during the study period rather than showing a consistent trend, but ultimately decreased from 19.3% in 1997 to 16.0% in 2007. This demonstrates that tertiary industry is not sufficiently promoting Beijing's economic development, and therefore plays a restrictive role in the current economy.

The driving weight of the primary manufacturing sector showed the most prominent decrease in component 6 (textile manufacturing), which decreased to 7.8% of the total for the sector, and component 23 (production and distribution of water) of the materials and energy transformation sector, which decreased to 0.3% of the total for the sector. These changes were the main reasons for the decreased overall weight of these sectors in 2007. Similarly to the pull weight results, the driving weights of components 12 (manufacturing of non-metallic mineral products) and 13 (smelting and pressing of metals) in the advanced manufacturing sector increased greatly, but the rate of increase reached more than 200%. The driving weight of other components in the advanced manufacturing sector also increased, such as components 14 (manufacturing of metal products), 16 (manufacturing of transportation equipment), 17 (manufacturing of electrical machinery and equipment), and 18 (manufacturing of communication equipment, computers, and other electronic equipment), which also increased by more than 100%. Their combined utility increased their driving weight during the study period. The inter-annual variability of components

Table 2
Changes in the ecological relationships from 1997 to 2007.

Year	Mutualism		Exploitation		Competition		Total no. of relationships
	Number	Percentage of total	Number	Percentage of total	Number	Percentage of total	
1997	84	15.91%	273	51.70%	171	32.39%	528
2000	71	13.45%	251	47.54%	206	39.02%	528
2002	69	13.07%	260	49.24%	199	37.69%	528
2005	72	13.64%	281	53.22%	175	33.14%	528
2007	85	16.10%	273	51.70%	170	32.20%	528

27 (financial industry), 29 (study and test development), and 31 (other services) of the tertiary industry sector was obvious, and changes in their combined driving weights effected the status of this layer in the overall ecological hierarchy. Therefore, these components should be a particular concern in efforts to adjust Beijing's economic structure.

4.2. Analysis of ecological relationships among the components

Our analysis revealed a total of 528 pairs of ecological relationships in Beijing's urban metabolic system. Table 2 summarizes the distribution of competition, exploitation, and mutualism relationships during the study period. Overall, exploitation relationships dominated, accounting for nearly 50% of the total and accounting for a relatively stable proportion of the total (ranging from 47 to 53%). The competition relationships were next most abundant, accounting for about 30% of the total (ranging from 32 to 39%), followed by mutualism relationships, which remained less than 20% throughout the study period (ranging from 13 to 16%). These results show the long-term dominance of exploitation relationships among the components. The mutualism relationships accounted for a consistently low overall proportion of the total, which indicates a need to improve the level of mutualism in Beijing's metabolic system.

Combining the components shown in Supplementary Table S1 into only eight sectors let us analyze the ecological relationships within each sector. Table 3 summarizes the numbers of each type of ecological relationship among the eight sectors in each year. These numbers are based on the sgn(**U**) values for the components in Supplementary Tables S6 to S10. Table 4 summarizes the distribution of the ecological relationships among the sectors. During the study period, the agriculture, construction, and domestic sectors were consistently dominated by self-mutualism relationships. In contrast, exploitation relationships dominated the advanced manufacturing sector throughout the study period, accounting for 50% of all the relationships. The tertiary industry sector alternated between competition and exploitation relationships. The mining sector was dominated by two relationships (mutualism and exploitation) in 1997, 2000, and 2005, but dominated by a single relationship (mutualism) in 2002 and 2007. The materials and energy transformation sector was dominated by mutualism relationships, except in 2000 (a mixture of competition and mutualism). For the primary manufacturing sector, competition relationships were dominant in the first 2 years, and exploitation was dominant in 2007, but 2002 and 2005 represented a mixture of the three relationships.

Table 3
The numbers of each type of ecological relationships in the eight sectors. A, agriculture; AM, advanced manufacturing; C, construction; D, domestic consumption; ET, materials and energy transformation; M, mining; PM, primary manufacturing; TI, tertiary industry.

Year	Relationship	Sector							
		A	M	PM	AM	ET	C	TI	D
1997	Exploitation	0	3	4	32	1	0	10	0
	Competition	0	0	6	17	2	0	11	0
	Mutualism	1	3	5	17	3	1	7	1
2000	Exploitation	0	3	4	32	0	0	8	0
	Competition	0	0	6	22	3	0	12	0
	Mutualism	1	3	5	12	3	1	8	1
2002	Exploitation	0	1	5	34	1	0	8	0
	Competition	0	2	5	20	2	0	13	0
	Mutualism	1	3	5	12	3	1	7	1
2005	Exploitation	0	3	4	34	1	0	8	0
	Competition	0	0	6	19	2	0	13	0
	Mutualism	1	3	5	11	3	1	7	1
2007	Exploitation	0	2	6	34	2	0	11	0
	Competition	0	1	4	19	0	0	10	0
	Mutualism	1	3	5	13	4	1	7	1

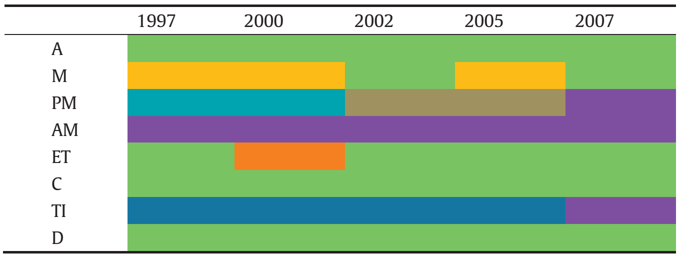
5. Conclusions

We integrated the use of physical input–output tables and ecological network analysis to analyze the structural and functional attributes of Beijing's urban metabolic system. By accounting for the embodied ecological element intensity when we compiled the physical input–output tables, we were able to define the hierarchical structure of Beijing's metabolic system and explore the functional relationships among the eight sectors and 32 components by building an urban metabolic network model. By identifying weaknesses in the system's ecological hierarchy and by identifying potentially damaging ecological relationships, our analysis provides a scientific basis for understanding and improving the development of Beijing's urban metabolic system.

We divided Beijing's industries into eight sectors, and established an ecological hierarchy for these sectors using their pull and driving weights. The results showed an irregular inverted pyramid structure and an irregular pyramid structure, respectively. Beijing's urban metabolic system is dominated by exploitation relationships, followed by competition relationships, and mutualism relationships are in the minority. This distribution is not conductive to the healthy future development of Beijing. From the perspective of the components within a sector that benefited from their mutual relationships, benefits were dominant in the agriculture, mining, advanced manufacturing, energy transformation, construction, and domestic sectors, whereas damaging relationships were dominant in the primary manufacturing and tertiary industry sectors. Overall, the eight sectors demonstrated positive utility, indicating good levels of mutualism for the overall system and for the relationships among components within a sector, but more work could be done to improve the proportion of mutualism relationships.

It is difficult to define the ecological hierarchy of a metabolic system composed of eight sectors. Starting from the ecological relationships among the components, with an emphasis on the competition, mutualism, and exploitation relationships to confirm the upstream and downstream distribution of benefits, we can objectively describe the ecological hierarchy. In the future, studying the positive and negative utilities of each type of ecological relationship by starting from each pair of components or each type of ecological relationship in the urban metabolic system can reveal weak components and provide support for developing policies and corrective measures targeted at the components that are facing problems.

Table 4
The distribution of all ecological relationships among the components inside the eight sectors. A, agriculture; AM, advanced manufacturing; C, construction; D, domestic consumption; ET, materials and energy transformation; M, mining; PM, primary manufacturing; TI, tertiary industry.



Note: mutualism; competition; exploitation; competition + mutualism; exploitation + mutualism; exploitation + mutualism + competition.

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Appendix A

If k represents an ecological element whose consumption intensity is embodied in the products of sector i, then ε_{kj}^{E} represents the consumption intensity of the k-th ecological element embodied in the products produced by sector j from the external environment (parts of China outside the system being studied). ε_{kj}^{M} represents the consumption intensity of the k-th ecological element embodied in the products produced by sector j from sectors outside of China.

The equilibrium equation for the value flows (Fig. 2a) is:

$$\sum_{j=1}^{n} x_{ji} + d_{Mi} + d_{Ei} + w_i = \sum_{j=1}^{n} x_{ij} + q_{iM} + q_{iL} + q_{iC} + q_{iE}. \quad (1)$$

The economic output of sector i is:

$$X_i = \sum_{j=1}^{n} x_{ij} + q_{iL} + q_{iE} + q_{iC} + q_{iM} - d_{Mi} - d_{Ei}. \quad (2)$$

The ecological element equilibrium equation for sector i (Fig. 2b) is then established as follows:

$$p_{ki} + r_{ki} + \sum_{j=1}^{n} \varepsilon_{kj} x_{ji} + \varepsilon_{kMi} d_{Mi} + \varepsilon_{kEi} d_{Ei} = \sum_{j=1}^{n} \varepsilon_{ki} x_{ij} + \varepsilon_{ki} q_{iM} + \varepsilon_{ki} q_{iL} + \varepsilon_{ki} q_{iC} + \varepsilon_{ki} q_{iE}$$

$$\sum_{k=1}^{m} z_{ki} + \sum_{j=1}^{n} \varepsilon_{kj} x_{ji} + \sum_{j=1}^{n} \varepsilon_{kj}^{M} d_{ji}^{M} + \sum_{j=1}^{n} \varepsilon_{kj}^{E} d_{ji}^{E} = \sum_{j=1}^{n} \varepsilon_{ki} x_{ij} + \varepsilon_{ki} y_i^{M} + \varepsilon_{ki} y_i^{L} + \varepsilon_{ki} y_i^{C} + \varepsilon_{ki} y_i^{E}$$

$$\sum_{k=1}^{m} z_{ki} + \sum_{j=1}^{n} \varepsilon_{kj} x_{ji} + \sum_{j=1}^{n} \varepsilon_{kj}^{M} d_{ji}^{M} + \sum_{j=1}^{n} \varepsilon_{kj}^{E} d_{ji}^{E} = \sum_{j=1}^{n} \varepsilon_{ki} x_{ij} + \varepsilon_{ki} y_i^{M} + \varepsilon_{ki} y_i^{L} + \varepsilon_{ki} y_i^{C} + \varepsilon_{ki} y_i^{E}$$

$$\sum_{k=1}^{m} z_{ki} + \sum_{j=1}^{n} \varepsilon_{kj} x_{ji} + \sum_{j=1}^{n} \varepsilon_{kj}^{M} d_{ji}^{M} + \sum_{j=1}^{n} \varepsilon_{kj}^{E} d_{ji}^{E} = \sum_{j=1}^{n} \varepsilon_{ki} x_{ij} + \varepsilon_{ki} y_i^{M} + \varepsilon_{ki} y_i^{L} + \varepsilon_{ki} y_i^{C} + \varepsilon_{ki} y_i^{E}. \quad (3)$$

The definitions for the parameters are defined in Table 1. Suppose that the consumption intensity of the k-th ecological element embodied in the products of sector i produced in Beijing, in China, and in the World are equal; that is, $\varepsilon_{ki} = \varepsilon_{ki}^{M} = \varepsilon_{ki}^{E}$, Eq. (3) then becomes:

$$p_{ki} + r_{ki} + \sum_{j=1}^{n} \varepsilon_{kj} x_{ji} = \varepsilon_{ki} \left(\sum_{j=1}^{n} x_{ij} + q_{iL} + q_{iC} + q_{iE} + q_{iM} - d_{Mi} - d_{Ei} \right). \quad (4)$$

That is:

$$p_{ki} + r_{ki} + \sum_{j=1}^{n} \varepsilon_{kj} x_{ji} = \varepsilon_{ki} X_i. \quad (5)$$

Appendix B. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2013.08.047.

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