

# Analysis of urban metabolic processes based on input–output method: model development and a case study for Beijing

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**Abstract** Discovering ways in which to increase the sustainability of the metabolic processes involved in urbanization has become an urgent task for urban design and management in China. As cities are analogous to living organisms, the disorders of their metabolic processes can be regarded as the cause of “urban disease”. Therefore, identification of these causes through metabolic process analysis and ecological element distribution through the urban ecosystem’s compartments will be helpful. By using Beijing as an example, we have compiled monetary input–output tables from 1997, 2000, 2002, 2005, and 2007 and calculated the intensities of the embodied ecological elements to compile the corresponding implied physical input–output tables. We then divided Beijing’s economy into 32 compartments and analyzed the direct and indirect ecological intensities embodied in the flows of ecological elements through urban metabolic processes. Based on the combination of input–output tables and ecological network analysis, the description of multiple ecological elements transferred among Beijing’s industrial compartments and their distribution has been refined. This hybrid approach can provide a more scientific basis for management of urban resource flows. In addition, the data obtained from distribution characteristics of ecological elements may provide a basic data platform for exploring the metabolic mechanism of Beijing.

**Keywords** urban ecology, urban metabolism, implied physical input–output table, ecological element intensity, Beijing

## 1 Introduction

Cities can be viewed as organisms, with the inputs of materials, energy, and food, and the outputs of wastes conceptualized as analogous to urban metabolic processes (Wolman, 1965). Researchers have been striving to enrich their study of these processes (e.g., Warren-Rhodes and Koenig, 2001; Codoban and Kennedy, 2008). With most of the existing studies examining the flows involved and evaluating the metabolism of typical cities by accounting for the inputs of materials and the outputs of wastes (Newcombe et al., 1978; Boyden et al., 1981; Warren-Rhodes and Koenig, 2001; Zhang et al., 2006a, b; Zhang and Yang, 2007; Codoban and Kennedy, 2008). Generally, their results only reflected the urban system’s external characteristics because the researchers examined the inputs, outputs, and the overall system as a whole (Zhang et al., 2011a, b, 2013). Until recently, few studies applied the urban metabolic approach to investigate the transfer and utilization of ecological elements within the system (Zhang et al., 2009a, b, c, 2010a, b, 2012; Li et al., 2012; Zhang, 2013).

For our study, we intend to introduce input–output analysis to evaluate the intermediate urban metabolic processes and the element flows between different compartments. Since the 1970s, input–output analysis, founded on input–output tables, has been widely used to account for ecological resources (quantified in terms of their monetary or physical value), such as water (Hite and Laurent, 1971), energy (Wright, 1974; Herendeen, 1978; Chen, 2011), or waste recycling (Liang and Zhang, 2012). Based on this analysis, the concept of embodied ecological element intensity, introduced by Zhou (2008), represented the amount of a resource that flows in or out of a compartment of a system. This approach was extended and applied in subsequent analyses (Chen et al., 2010; Chen and Chen, 2010; Chen, 2011). Some scholars have used other unified indicators like solar emergy, cosmic emergy,

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and exergy to systematically measure individual ecological elements in the metabolic process (i.e., the materials, information, or energy that flow through a metabolic system). The resources analyzed in these studies include energy (Chen and Chen, 2011c; Chen and Chen, 2013), water (Zhou et al., 2010), carbon (Chen and Chen, 2011b; Su and Ang, 2011, 2013; Chen et al., 2013), and wastes (Li and Chen, 2013), while other studies focus on different ecological elements in the metabolic system (Chen and Chen, 2010, 2011a; Chen et al., 2010). Furthermore, the input–output analysis has been used to investigate economies at the global scale (Chen and Chen, 2011a, c, 2013), national scale (Chen et al., 2010; Chen and Chen, 2010), and urban scale (Chen et al., 2013; Guo and Chen, 2013; Li and Chen, 2013; Li et al., 2013). However, data on the physical quantity of the resource flows are not always available. In that case, researchers often convert the monetary value into physical quantities measured with mass or energy units by using an appropriate conversion factor. Thus, the flows are not the actual resource flows, but instead are often referred to as virtual or “implied” ecological flows (Chen, 2011). The implied ecological element intensities for the whole system concerned, and also for each compartment, are of great significance from the perspectives of ecology and ecological economics, because they provide the basis for macroeconomics studies and the distribution of ecological elements within a system. Previous studies have only analyzed these intensities for a few key elements, such as water, energy, and some greenhouse-effect gases (e.g., Wright, 1975; Xu, 2010). Based on the previous studies, we here adopt the input–output analysis to account for a wider range of ecological elements, including agricultural products (with crops and animal products treated separately), forest products, energy minerals, metal minerals, non-metal minerals, inputs of fresh water, and emission of wastes. We also combined this approach with material-flow and ecological network analysis to fully calculate the ecological elements transferred between the industrial compartments of an urban metabolism.

Patten (1978) developed the ecological network analysis based on input–output tables, which is an effective method for structural analysis and can be used to systematically analyze the flows of materials and energy within an ecosystem (Finn, 1976). This ecological network analysis was later applied in numerous studies. However, most existing studies examined only a single sector, such as industry (Chen, 2003), fishery (Walters et al., 1997; Pauly et al., 1998), energy (Zhao, 2006; Zhang et al., 2010b), or water resources (Bodini and Bondavalli, 2002; Li et al., 2009; Zhang et al., 2010a), or only a single element or product, such as aluminum (Bailey et al., 2004a) or carpeting (Bailey et al., 2004b). Few have examined the structure of a metabolic system by combining an input–output analysis with an ecological network analysis (Yang et al., 2012).

In this paper, we used monetary input–output tables to perform a case study of Beijing using data of 1997, 2000, 2002, 2005, and 2007. By combining these data with the embodied ecological element intensity databases, we accounted for the consumption of ecological elements via urban metabolic processes, and compiled the corresponding implied physical input–output tables, which represented the flows of multiple ecological elements. The metabolic system was then divided into 32 compartments, and the flows were classified into five types according to the total ecological intensity and the balance between the direct and indirect ecological intensities. We then analyzed the direct and indirect inputs for each compartment. We refined the description of the multiple ecological elements that transfer between Beijing’s industrial compartments and domestic compartments, and then analyzed the distribution. Our results provide a more scientific basis for management of the urban metabolic system’s flows. The basic data on the ecological elements distribution within the system also supports analyses of the concerned urban metabolic systems.

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## 2 Methods and data

### 2.1 Compilation of the implied physical input–output tables

Using a “top-down” input–output method, we described the urban metabolic system using monetary flow details because it was impossible to examine a wider range of biophysical flows due to data availability. On the basis of the already existing embodied ecological element intensities, we can transform the monetary input–output tables into implied physical input–output tables. This intensity factor represents the quantity of an ecological element per monetary unit value embodied in the element exchanged within the system, and therefore it allows us to estimate the amount of ecological elements consumed by each sector or compartment of the system (Chen, 2011). The quantity of the ecological element can then be estimated by multiplying the ecological element intensity by the corresponding economic flow, thus generating the implied physical input–output tables.

An input matrix with the initial ecological elements is first developed to serve as the monetary input–output network of the primary elements. We then constructed input–output tables that combined both monetary and physical flows of these inputs, which formed the basis for analyzing all subsequent flows among the compartments. The resource flows in each year between compartments forms an  $n \times n$  economic input–output table, where  $n$  represents the number of compartments in the system. In Beijing, the number of  $n$  equals to 32. The input matrix for the ecological elements is  $(m + s) \times n$ , where  $m$  represents the number of resource element types and  $s$  represents the number of waste types. The input–output tables can then

be divided into a value module and a material module. We can thereby construct material-value input–output tables that capture both socioeconomic and environmental flows (see Table 1).

The equilibrium equations for the ecological elements can be developed by extracting the data for any compartment  $i$ . Based on the value of the flows into and out of compartment  $i$  (Fig. 1(a)), a value equilibrium equation for compartment  $i$  can be modified according to Chen (2011). Here, it is a process used for calculating implied ecological intensities. The implied physical input–output table based on the material flow analysis includes 20 types of resources and 6 types of waste. Thus, it can reflect the ecological elements needed by the industries. Furthermore, it quantifies the intensity of ecological elements of various industrial compartments by ecological network analysis. The equilibrium equation for the value flows (Fig. 1(a)) is

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

where  $x_{ji}$  represents the value flow from compartment  $j$  to compartment  $i$ ;  $d_{Mi}$  is the value flow into compartment  $i$  from compartments outside of China;  $d_{Ei}$  is the value flow from the external environment (i.e., regions outside Beijing) into compartment  $i$ ;  $w_i$  is the non-industrial input value flow of labor into compartment  $i$ ;  $x_{ij}$  is the value

flow from compartment  $i$  to compartment  $j$ ;  $q_{iM}$  is the value flow from compartment  $i$  to compartments located outside of China;  $q_{iL}$  is the final consumption value flow for compartment  $i$  within the system itself;  $q_{iC}$  is the total capital formation in the system itself; and  $q_{iE}$  represents the value flow from compartment  $i$  to the external environment. Table 2 summarizes how these and other parameters fit within our overall model of the system.

Based on these flows, we can establish the ecological element equation for compartment  $i$ . In addition to those ecological elements directly consumed by compartment  $i$ , the compartment indirectly consumes ecological elements embodied in intermediate products from other compartments. Therefore, the embodied effect is a result of flows transferring from one compartment to another, happens. If  $k$  represents the embodied element intensity of the product from compartment  $i$ , then  $\varepsilon_{ki}$  represents the intensity of the  $k^{\text{th}}$  ecological element embodied in the products produced by compartment  $i$ . The  $w_i$  parameter in the input–output tables is an added value, for which  $p_{ki}$  represents the value of the initial ecological element input into the system, so that the implied ecological element of  $w_i$  equals 0 (Duchin, 2009). As wastes ( $r_{ki}$ ) are treated as inputs for certain compartments, the value should be less than 0.

In light of a sub-model proposed by Su and Ang (2013) which may account for the effects of competition between providers from different regions, we are able to obtain relatively accurate data on imports and exports from multiple regions, as well as resource transfers. The competitive input–output tables, in which the effects of competition among providers from different regions are

**Table 1** The basic form of the implied physical input-output table

Input		Compartment				Output					
		1	2	...	$n$	Consumption	Capital formation	Transfer-in	Imports	Transfer-out	Exports
Compartment	1	$x_{11}$	$x_{12}$	...	$x_{1n}$	$q_{1L}$	$q_{1C}$	$q_{E1}$	$q_{M1}$	$q_{1E}$	$q_{1M}$
	2	$x_{21}$	$x_{22}$	...	$x_{2n}$	$q_{2L}$	$q_{2C}$	$q_{E2}$	$q_{M2}$	$q_{2E}$	$q_{2M}$
	...	...	...	...	...	...	...	...	...	...	...
	$n$	$x_{n1}$	$x_{n2}$	...	$x_{nn}$	$q_{nL}$	$q_{nC}$	$q_{En}$	$q_{Mn}$	$q_{nE}$	$q_{nM}$
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 $m+s$	$r_{(m+s)1}$	$r_{(m+s)2}$	...	$r_{(m+s)n}$						

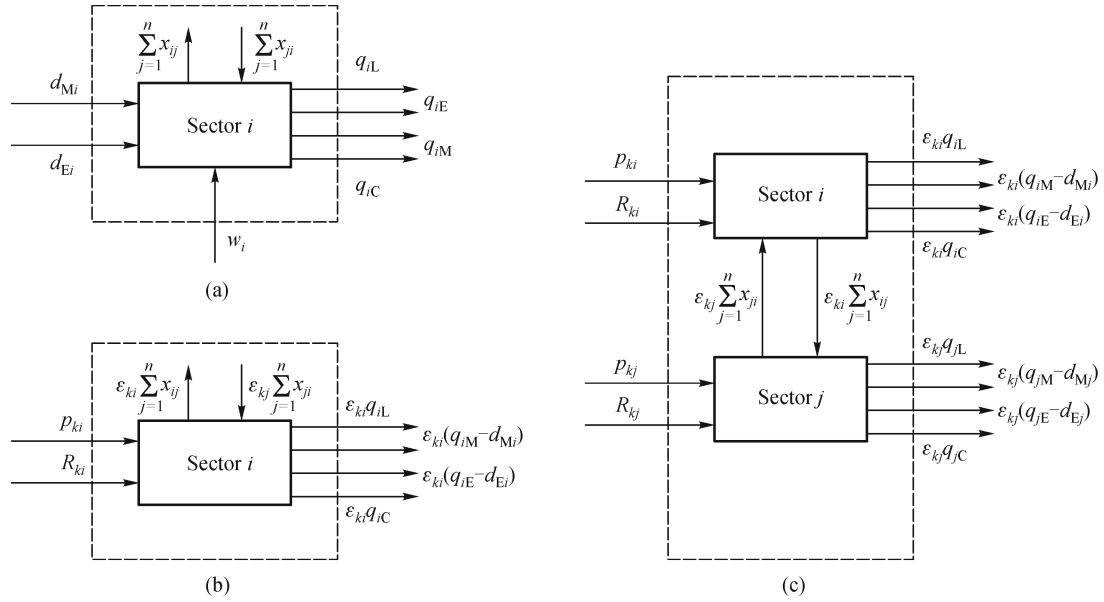


Fig. 1 The accounting diagram of monetary flow and physical flow of  $i^{th}$  compartment.

Table 2 The correspondence between the original compartments and the types of resources or wastes

Type of resource	Sub-type	Industry number*	Type of waste	Industry number*
Crops	Vegetables	1	Wastewater	2–23, 32
	Cereals	1	SO <sub>2</sub>	2–23
	Cotton	1	Dust	2–23
	Oil plants	1	Smoke	2–23
	Fruits	1	Solid wastes	2–23, 32
Forest products	Timber	1	CO <sub>2</sub>	2–26, 32
Animal products	Cattle	1		
	Horses	1		
	Mules	1		
	Donkeys	1		
	Sheep	1		
	Pigs	1		
	Poultry	1		
	Eggs	1		
	Honey	1		
	Milk	1		
	Energy minerals	Raw coal	2	
Metal minerals	Iron ore	4		
Non-metallic minerals	Cement	3		
Fresh water		2–23		

\* See compartment name in Appendix for the meaning of industry number.

ignored, are employed. To distinguish the sources of imported and exported ecological intensities, it is necessary to account for the ecological intensities at global and national scales, which requires considerable supporting data. However, the latest available input–output table for flows among regions in China is that of 2007, which does

not match the study period. In this paper we focused on the economic and technical relationships among the industrial compartments in Beijing. As a result, the transfer-in and import data can be simplified. Indeed, the approaches, such as emissions embodied in bilateral trade (EEBT) and multi-regional input–output (MRIO) in Peters (2008) and Su and

Ang (2011) are commonly used to measure embodied emissions at the national level. The EEBT approach applies the single-region input–output (SRIO) model to each entity (or country), while the MRIO approach applies the full MRIO model to all entities (or all countries) (Su and Ang, 2011). In addition, the study of a specific region within a country requires spatial disaggregation as discussed in Su and Ang (2010), which further presents a hybrid approach for such regional embodiment. Due to the data constraints, and this paper mainly analyzes the relationship between internal compartments, our results should be treated as simplified values.

We adopted competitive input–output tables to process the transfer-in and import data, and established the equilibrium equation for ecological elements based on the net value of resource transfers (resources transferred out minus those transferred in) and the net exports (exports minus imports).

The economic output of compartment  $i$  ( $X_i$ ) is

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

The ecological element equilibrium equation for compartment  $i$  (Fig. 1(b)) is then established as follows:

$$\begin{aligned} p_{ki} + r_{ki} + \sum_{j=1}^n \varepsilon_{kj} x_{ji} \\ = \sum_{j=1}^n \varepsilon_{ki} x_{ij} + \varepsilon_{ki} q_{iL} + \varepsilon_{ki} q_{iC} + \varepsilon_{ki} (q_{iE} - d_{Ei}) \\ + \varepsilon_{ki} (q_{iM} - d_{Mi}), \end{aligned} \quad (3)$$

where  $p_{ki}$  represents the flows of the  $k^{\text{th}}$  resource element into compartment  $i$ ;  $r_{ki}$  represents the  $k^{\text{th}}$  waste emitted by compartment  $i$ .

Eq. (3) can be simplified as follows:

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

That is

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

If we assume that  $h_{ji} = x_{ji}$ ,  $\mathbf{P} = [p_{ki}, r_{ki}]_{(m+s) \times n}$ , and  $\boldsymbol{\varepsilon} = [\varepsilon_{ki}]_{m \times n}$ , when  $i = j$ ,  $u_{ji} = X_i$  whereas when  $i \neq j$ ,  $u_{ji} = 0$  for an urban metabolic system that includes  $n$  compartments and  $m + s$  types of ecological elements, Eq. (5) can be

presented in the matrix form:

$$\mathbf{P} + \boldsymbol{\varepsilon} \mathbf{H} = \boldsymbol{\varepsilon} \mathbf{U}. \quad (6)$$

Then,

$$\boldsymbol{\varepsilon} = \mathbf{P}[\mathbf{U} - \mathbf{H}]^{-1}, \quad (7)$$

where  $\boldsymbol{\varepsilon}$  is the embodied ecological element intensity matrix for the compartments. If the transformed value flow is determined by each compartment, we can multiply the embodied ecological element intensity factor of one specific compartment by the flow to compute the quantity of implied ecological elements in the value flow. Based on these calculations, we can establish the implied physical input–output matrix, which reflects the relationships involved in the utilization of the flows of ecological elements between compartments. The implied physical input–output tables include two parts: an intermediate monetary input–output table that accounts for the flows according to the traditional method for input–output tables, and an ecological input table. Here, “resources” refer to the initial input resources for a compartment, and indicate the ecological elements obtained from the natural ecosystem. In our analysis, we accounted for four resource types: 1) biological resources (e.g., crops, plants, and farming), 2) energy (mining), 3) non-energy minerals (metals and non-metals), and 4) water. These four types can be further subdivided into 20 specific materials. In addition, there are six types of wastes (wastewater, sulfur dioxide, smoke, dust, solid wastes, and carbon dioxide). Table 2 clarifies which compartments provided data for each type of resource or waste.

## 2.2 Urban metabolic network model

In this study, we analyzed the urban metabolism of Beijing in 1997, 2000, 2002, 2005, and 2007 and developed implied physical input–output tables from economic value flow data for the years concerned. According to the monetary input–output tables established by the government, there are 42 compartments, forming a  $42 \times 42$  matrix of flows between each pair. We combined these compartments into a smaller group of 31 compartments plus a domestic consumption compartment, based on the similarity of their products and the unity of their time series in the implied physical input–output tables (see Appendix). The data used for the ecological elements were mainly obtained from statistics published in the *Beijing Statistical Yearbook*, *Beijing Water Resources Bulletin*, *China Mining Statistical Yearbook*, *China Statistical Yearbook on the Environment*, *China Statistical Yearbook*, and *China Environment Yearbook*, in addition to some other publications. Because the units differed among the various flows, we converted all the raw data into units of metric tons (t) to permit direct flow comparisons.

Beijing’s urban metabolic system represents a socio-

economic system composed of both industrial (production) and consumption compartments. The system's environment includes both the natural environment within the city's administrative boundary and the economic entities and natural environment located outside the administrative boundary. Because the environment provides the support required by the socioeconomic system, studies on the urban metabolic system should consider more than just the exchanges of materials and energy among the industrial compartments and between the industrial compartments and the consumption compartment. Consequently, it is vital that these studies consider not only the environmental inputs, but also the environmental outputs.

The compartments mainly include domestic and government consumption, which represent the final consumption compartments in the implied physical input-output tables. In the present study, we did not explicitly include government consumption as a separate compartment; but instead accounted for its effects on consumption. Based on the division of the system's compartments and the relationships among the compartments in the implied physical input-output tables, we defined the urban metabolic network model illustrated in Fig. 2. In this network model, nodes represent the different compartments, and directional lines between two nodes stand for the exchange of materials between the compartments.  $f_{ji}$  represents the flow from  $i$  to  $j$ . By using the input-output method, we can define the inputs and outputs for the exchanges both within the environment and those of ecological elements between the system's compartments.

In this analysis,  $z_i$  represents the input flow from the external environment into compartment  $i$ , and  $y_i$  represents the output flow from compartment  $i$  into the external environment.

In addition to the direct consumption of ecological elements, the urban metabolism also indirectly consumes

ecological elements in the process of utilizing intermediate products. From the perspective of life-cycle analysis, the consumption of ecological elements should account for the ecological elements consumed throughout the entire chain (Lenzen, 1998; Reinders et al., 2003). Using steel production process as an example, in addition to direct electricity consumption, this process also indirectly consumes electricity generated from coal, as well as pig iron, refractory brick used in the smelter, and manufactured metallurgical equipment. For instance, wooden mine timbers are used in the production of coal (i.e., to support the tunnels). Additionally, the electricity consumed in both mine timber production and in the process of washing iron ore should be considered. Therefore, the steel-production process includes not only the direct, but also indirect, electricity consumption during the production of these additional products affecting the sum of total electricity consumption by steel production.

We can then conceptualize the exchanges of ecological elements among the six sectors shown in Fig. 3. The direct consumption of ecological elements in compartment 6 is added to the indirect consumption of ecological elements through the paths with a length of up to 5, by which the indirect consumption of ecological elements consumed by the other five compartments is accounted for (Fig. 3).

For the urban metabolic system, the flow of ecological elements includes both the initial consumption of ecological elements and the ecological elements implied in the production of intermediate products. The total ecological element consumption can be calculated by ecological network flow analysis (Finn, 1976). Ecological network flow analysis is based on the total embodied flux ( $T$ ). Using the ratio of the embodied exchange flow  $f_{ij}$  to the total embodied ecological flux into node  $i$  ( $T_i$ ), we can calculate the elements ( $g'_{ij}$ ) of the nondimensional embodied energy exchange intensity matrix,  $G'$ :

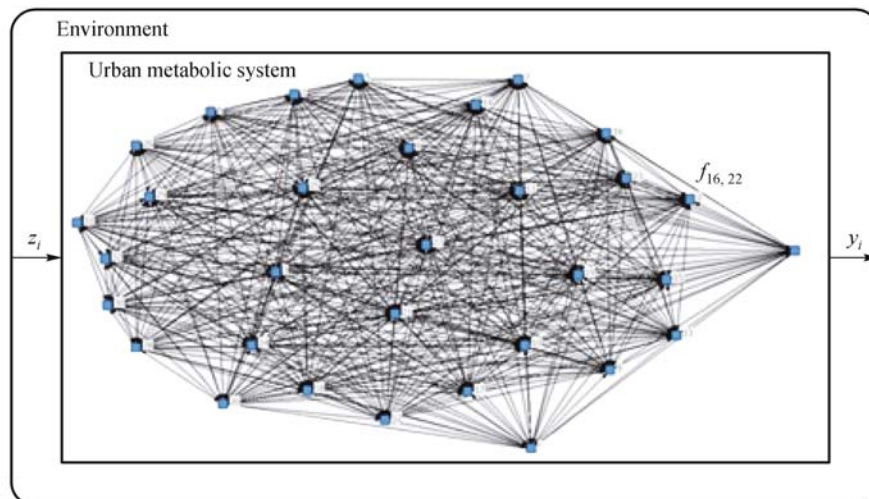


Fig. 2 The urban metabolic network model.

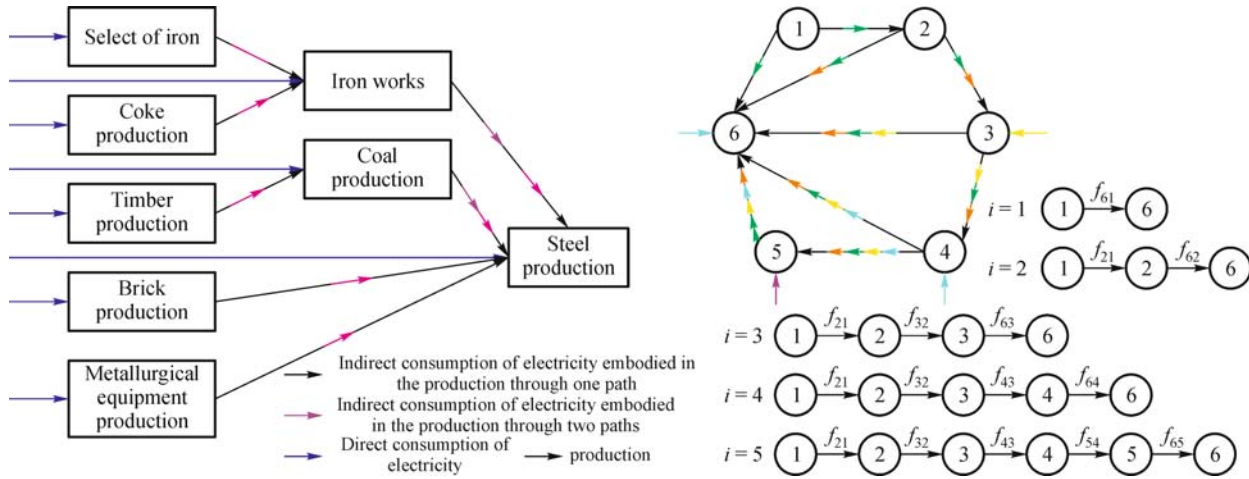


Fig. 3 Analysis of the direct and indirect processes in the steel production process.

$$g'_{ij} = f_{ij}/T_i, \tag{8}$$

where  $T_i$  is the total input flux of the embodied ecological element into node  $i$ , and represents the total flows from other compartments and the external environment ( $z_i$ ) into node  $i$ :

$$T_i = \sum_{j=1}^n f_{ij} + z_i. \tag{9}$$

Using  $\mathbf{G}'$ , we can calculate the nondimensional indirect energy intensity matrix  $\mathbf{N}'$  ( $n'_{ij}$ ) and  $\mathbf{G}'$  matrices for each possible metabolic length ( $l$ ):

$$\begin{aligned} \mathbf{N}' = (n'_{ij}) &= (\mathbf{G}')^0 + (\mathbf{G}')^1 + (\mathbf{G}')^2 + (\mathbf{G}')^m \\ &+ \dots \\ &= (\mathbf{I} - \mathbf{G}')^{-1}, \end{aligned} \tag{10}$$

where  $(\mathbf{G}')^0$  is a self-feedback matrix that reflects flows that occur within each compartment,  $(\mathbf{G}')^1$  is the flow intensity matrix when the metabolic flow follows a path directly between two compartments, so that the length equals 1 (i.e.,  $l = 1$ ). The higher value of  $\mathbf{G}'$  reflects longer flow intensities of different metabolic flows; for example,  $(\mathbf{G}')^2$  reflects flows of metabolic length 2 and  $(\mathbf{G}')^m$  reflects flows of metabolic length  $m$  ( $m \geq 2$ ).

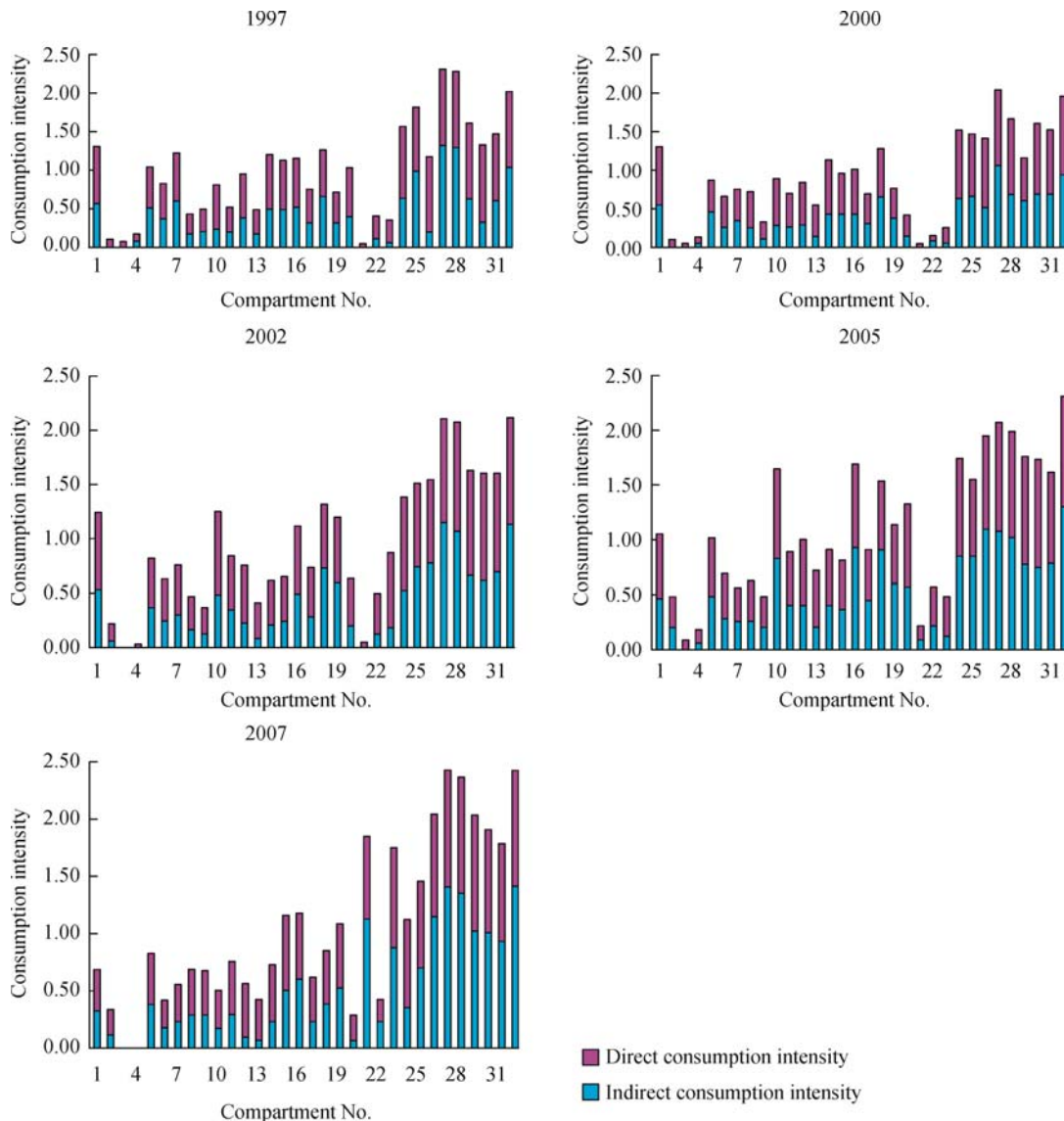
The indirect flow equals the total flow minus the direct flows. Based on the total ecological element flow-intensity matrix, we can calculate the indirect ecological element flow intensity matrix as **Indirect** =  $\mathbf{N}' - \mathbf{I} - \mathbf{G}'$  (Fath and Grant, 2007). By comparing the direct and indirect ecological element flow-intensity matrices, we can obtain the balance between the direct and indirect inputs, which can be used to analyze the characteristics of the ecological elements of each compartment. This analysis can be used to help increase the efficiency of the compartments.

### 3 Results and discussion

The direct and indirect ecological element consumption intensities are shown in Fig. 4. The total ecological element intensity increased throughout the period concerned, reaching its maximum value in 2007. The gap between direct and indirect consumption was narrow, and the characteristics of the distribution among compartments are obvious: the compartments with high consumption intensities are tertiary industries with some advanced processing and manufacturing compartments. The consumption intensities of these compartments increased with a growth rate of 21.7% over 10 years. Tertiary industries have the highest intensities, especially for the *Financial industry* (No. 27) and *Real estate trade* (No. 28), all with values higher than 2.0. This is because the money trading process (i.e., the exchange of intermediate products) reflects the consumption and transfer of materials and energy. The high value of this trade implies an equally high intensity of ecological element consumption.

The consumption intensity of *Agriculture* (No. 1) was relatively high due to its massive use of natural ecological elements in a natural system. The consumption intensities were smallest for three industries (*Mining and washing of energy minerals* (No. 2), *Mining and processing of metal ores* (No. 3), and *Mining and processing of non-metal ores* (No. 4)), all with values less than 0.5. This finding relates to the resource utilization pattern in Beijing. The input of such ecological elements is mainly from some other places within China, and regions located outside China, yet few of the inputs are from its domestic compartments.

Based on the magnitude of the gap between the direct and indirect consumption intensities, we divided the 32 compartments into five categories with distinctive direct and indirect consumption. First, the ecological intensities of consumption are considered and all the compartments are divided into three types. To do so, we calculated the



**Fig. 4** The annual direct and indirect consumption intensity of the ecological elements for each compartment.

median gap and then arranged the implied ecological element intensities of each compartment in each year in descending order. Next, we divided the overall dataset into three groups according to the intensities: “highest” total consumption ( $\geq 1.5$ ), high total consumption (0.5 to 1.5) and low total consumption ( $\leq 0.5$ ). We then subdivided the first two groups based on the relative magnitudes of the direct and indirect consumption intensities (Table 3). This approach provides insights into compartments which should be regulated and provides a basis for tracing upstream industrial chains during its life cycle.

Direct consumption was generally larger than indirect consumption (Table 3), as in the cases of 1-agriculture and some primary and advanced processing and manufacturing compartments (5–17, 19–20). The indirect intensities of the tertiary industries (25–31) and consumption compartments (32) were larger than the direct intensity. This reflects the positions of these compartments within the

ecological network; they are at the end of the industrial chains, leading to high indirect consumption. However, the total consumption was also high. We observed the following trends in Table 3:

1) The number of compartments with “highest” total consumption ( $\geq 1.5$ ) and higher indirect consumption increased from two in 1997 to nine in 2007. The growth reflects the economic development that has occurred in Beijing, especially the relationships between tertiary and other compartments. In contrast, the number of compartments in which indirect consumption was less than direct consumption decreased to 0 in 2007.

2) Few compartments had both high total consumption (between 0.5 and 1.5) and higher indirect consumption. There were only two such compartments in the first three years. The indirect consumption by *Manufacturing of communication equipment, computers* (No. 8), and other electronic equipment was higher than its direct consump-

**Table 3** Classification of the compartments according to the direct and indirect consumption intensities ( $e$  represents the total consumption intensity)

	Characteristics	Included compartments*				
		1997	2000	2002	2005	2007
Higher total consumption; indirect is higher than direct consumption	$e > 1.5$ ; $eID - eD > 0$	24, 29	<b>27</b>	26, 27, 28, 32	10, 16, 18, 25, <b>26, 27</b> , <b>28, 32</b>	21, 23, <b>26</b> , <b>27, 28, 29</b> , 30, 31, <b>32</b>
Higher total consumption; indirect is lower than direct consumption	$e > 1.5$ ; $eID - eD < 0$	25, 27, 28, 32	24, 28, <b>30</b> , <b>31, 32</b>	25, 29, <b>30</b> , <b>31</b>	24, 29, <b>30</b> , <b>31</b>	
High total consumption; indirect is higher than direct consumption	$0.5 < e < 1.5$ ; $eID - eD > 0$	<b>5, 18</b>	<b>18, 29</b>	<b>18, 19</b>	19	
High total consumption; indirect is lower than direct consumption	$0.5 < e < 1.5$ ; $eID - eD < 0$	<b>1, 6, 7, 10</b> , <b>11, 12, 14</b> , <b>15, 16, 17</b> , <b>19, 20, 26</b> , 27, 30, 31	<b>1, 5, 6, 7, 8</b> , <b>10, 11, 12</b> , <b>13, 14, 15</b> , <b>16, 17, 18</b> , <b>19, 25, 26</b> , 29	<b>1, 5, 6</b> , <b>7, 10, 11</b> , <b>12, 14, 15</b> , <b>16, 17, 18</b> , <b>19, 20, 23</b> , 24	1, 5, 6, 7, <b>8, 11, 12</b> , 13, 14, 15, <b>17, 19, 20</b> , 22	<b>1, 5, 7, 8, 9</b> , <b>10, 11, 12</b> , <b>14, 15, 16</b> , <b>17, 18, 19</b> , 24, 25
Low total consumption	$e < 0.5$	<b>2, 3, 4, 8, 9</b> , <b>13, 21, 22</b> , <b>23</b>	<b>2, 3, 4, 9, 21</b> , 20, <b>22, 23</b>	<b>2, 3, 4, 8, 9</b> , <b>13, 21, 22</b>	<b>2, 3, 4, 9</b> , <b>21, 23</b>	<b>2, 3, 4, 6</b> , <b>13, 20, 22</b>

Note: Boldfaced numbers indicate compartments that belonged to the same category for  $\geq 3$  years. \* See compartment name in Appendix.

tion in 1997, 2000, and 2002. In 2005, the indirect consumption by the high-technological electronics industry was higher than its increasing total direct consumption. A large proportion of the compartments (No. 14–18) had high total consumption and its indirect consumption was less than its direct consumption. These compartments include 1-agriculture and some processing and manufacturing compartments (i.e. 6–7 and 10–12). These compartments are still leading sectors or industries in Beijing, with intensive consumption of ecological elements. The proportion of direct consumption for these compartments is almost 60%. Therefore, increasing the efficiency of ecological element utilization by these compartments and then reducing their direct consumption of inputs will be important management priorities.

3) The intensities of low-consumption compartments are less than 0.5, and their direct consumption is higher than their indirect consumption. These compartments include the *Mining and processing of metal ores* (No. 3), *Mining and processing compartments of non-metal ores* (No. 4), *Production and distribution of electric power and heat* (No.21), *Production and distribution of gas* (No. 22), and *Production and distribution of water* (No. 23). The low consumption of domestic resources by these compartments is due to the low quantity of exploitation and enrichment of these resources in Beijing. Instead these compartments rely on inputs from places that are outside the system. The reliance on these inputs will impose pressure on the system concerned. Therefore, it will be necessary to raise the sense of responsibility for these external impacts, reduce the amount of resources consumed, as well as their intensity, and exploit new materials to promote more sustainable development.

## 4 Conclusions

1) Based on the integration of input–output tables and the ecological network analysis, we have articulated the ecological element flows between the many compartments of an urban metabolic system. Thus, this approach can provide a more scientific basis for management of resource utilization in these compartments. Our results also provide basic data for analyzing the mechanisms of the urban metabolic system.

2) By dividing the overall metabolic system into many compartments, we were able to detect differences in their metabolic characteristics. The compartments with high consumption intensities are mostly tertiary industries at the end of industrial chains. The compartments with low consumption intensities are mostly primary industries, such as the mining and processing compartments, as well as some compartments involved in the transformation of materials from other compartments. In some compartments with high total consumption, such as agriculture and some processing and manufacturing compartments, the direct consumption is higher than the indirect consumption. For these compartments, increasing the efficiency of the direct consumption of ecological elements is imperative. In contrast, indirect consumption is higher than direct consumption for compartments such as those for manufacturing communication equipment, computers, and other electronic equipment, because their consumption of ecological elements must move through the entire industrial chain during the life cycle of these compartments' products. Therefore, the ecological element input of all previous steps in the chain should be reduced to control consumption when it is necessary.

3) This work represents a preliminary study on the metabolism of urban ecological elements; therefore, there is much room for future improvements. First, we did not distinguish inputs that come from other regions located within China from those imported from regions outside of China. Second, since detailed waste emission data are not available for each industry, we used the national average rather than that of Beijing, which would decrease the accuracy of our results. Moreover, due to the data constraints, we only focus on the relationship between internal compartments with these results treated as approximate values. The need to obtain more precise and

accurate values is also key and should be solved in future research. It is important to use data from multiple regions in the modeling and analysis, given international feedback affects the result in regard to trade between regions.

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### Appendix: Names of the eight sectors and the compartments within each sector.

Sector	Compartment No.	Compartment name
A(agriculture)	1	<i>Agriculture</i>
M(mining)	2	<i>Mining and washing of energy minerals</i>
	3	<i>Mining and processing of metal ores</i>
	4	<i>Mining and processing of non-metal ores</i>
PM(primary manufacturing)	5	<i>Manufacturing of foods and processing of tobacco</i>
	6	<i>Manufacturing of textiles</i>
	7	<i>Manufacturing of clothing and of leather, fur, feather, and other fiber products</i>
	8	<i>Processing of timber and manufacture of furniture</i>
	9	<i>Manufacturing of paper, and printing and manufacture of cultural and educational articles</i>
AM(advanced manufacturing)	10	<i>Processing of petroleum, coking, and processing of nuclear fuel</i>
	11	<i>Chemical industry</i>
	12	<i>Manufacturing of non-metallic mineral products</i>
	13	<i>Smelting and pressing of metals</i>
	14	<i>Manufacturing of metal products</i>
	15	<i>Manufacturing of general-and special-purpose machinery</i>
	16	<i>Manufacturing of transportation equipment</i>
	17	<i>Manufacturing of electrical machinery and equipment</i>
	18	<i>Manufacturing of communication equipment, computers, and other electronic equipment</i>
	19	<i>Manufacturing of measuring instruments and machinery for cultural activities and office work</i>
ET (materials and energy transformation)	20	<i>Art and other manufactures</i>
	21	<i>Production and distribution of electric power and heat</i>
	22	<i>Production and distribution of gases</i>
C(construction)	23	<i>Production and distribution of water</i>
	24	<i>Construction</i>
TI(tertiary industry)	25	<i>Transportation and storage</i>
	26	<i>Postal services</i>
	27	<i>Financial industry</i>
	28	<i>Real estate trade</i>
	29	<i>Study and test development</i>
	30	<i>Integrated technical services</i>
	31	<i>Other services</i>
D(domestic sector)	32	<i>Domestic sector</i>

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