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Synergism analysis of an urban metabolic system: Model development and a case study for Beijing, China

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ABSTRACT

The efficiency of urban metabolic processes depends on the degree of mutualism of these processes throughout the metabolic system and on the value gained by each compartment within the system. This can be assessed by means of ecological network-based synergism analysis. In this paper, we used material-flow accounting methods to account for the exchanges of resources and wastes among the compartments of an urban system. Using a seven-compartment urban metabolic network model of Beijing, China, as a case study, we examined the degree of synergism of the compartments, determined the nature of the resulting ecological relationships, and determined the flow of utility to each compartment within the system. The results revealed which types of ecological relationship contributed most to the system (here, exploitation) and identified the key compartments that decreased the system's degree of synergism. The results provide theoretical and empirical support for the development of policies designed to promote healthy development of Beijing's urban metabolic system.

1. Introduction

The concept of urban metabolism was proposed by Wolman (1965) to describe the flows of materials and energy within an urban system and between the system and its environment. Because cities are artificial systems that use materials and energy inefficiently compared with natural systems, they face endless environmental problems related to the flows of urban resources, and these problems have made the study of urban metabolism one of the hot topics in the field of urban research (Girardet, 1990; Kennedy et al., 2007; Warren-Rhodes and Koenig, 2001; Zhang et al., 2006a,b, 2009a,b, 2011a,b; Zhang, 2013).

Early research on urban metabolism was based on accounting for the inputs of materials and energy and the outputs of wastes, and used methods such as index analysis (Codoban and Kennedy, 2008; Huang et al., 2006; Warren-Rhodes and Koenig, 2001), model development (Girardet, 1990; Newman and Kenworthy, 1999), and other means to evaluate the overall situation of an urban metabolism. Because these studies focused on analyzing the overall inputs and outputs of some typical cities, they were typically "black box" analyses that ignored the inner workings of the system. Unfortunately, this approach conceals the internal aspects of the system that are working inefficiently and that require improvement. To provide more profound insights into the flows within an urban system, Zhang et al. (2009a) proposed an urban metabolic network model that explicitly examined the compartments within the black box by defining the system's key compartments and the flows between compartments. The results of this approach established a comprehensive network model for the urban metabolism that revealed key details of the resource flows within the system (Zhang et al., 2009a), and subsequent research established network models for urban water metabolism (Zhang et al., 2010a) and energy metabolism (Zhang et al., 2010b). These studies provided preliminary insights into an urban system's metabolic processes, but provided insufficient insights into the degree of synergism within the system, which is related to the benefits that arise from the intrinsic interrelationships within the urban metabolic system.

Synergism analysis provides an important tool for investigating complex networks such as those that characterize a city (Andersson and Westbye, 1970; Carey et al., 1990; Casida et al., 1966; Salvador, 2000). The word "synergism" was initially applied in ecology, and referred to a phenomenon in which the effect caused by two or more species was greater than the sum of the effect of each species (Gugumus, 2002; Guo et al., 2009; Haken, 1977). In particular, synergism can reflect the utilities conferred by the relationships among

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species in the same environment (Corning, 1983). Synergism can be used for analyses at scales ranging from small (e.g., the relationships between genes or species; Normand, 1986) to very large (e.g., the relationships between climate change and ecology; Schneider and Root, 2004). In the field of socioeconomics, synergism has also been applied to analyses of the effects of decisions about how to allocate resources and the scope of a business or joint efforts between industrial sectors in which an outcome emerges such that "1 + 1 > 2" (Ahmad and Tyrrell, 1986; Berenbaum, 1985; Sühnel, 1990).

Because synergism studies require an understanding of the relationships within a system, ecological network analysis is an effective tool for defining the system that will be subjected to synergism analysis. Patten (1991) proposed the synergism analysis method during the process of developing methods for ecological network analysis. He used a synergism index (discussed in more detail in the Section 2) to represent the utility obtained from the interrelationships among the compartments of a system and the synergistic degree of the whole system. For example, Chen and Chen (2012) established an ecological network model of the carbon metabolism of Vienna (Austria), and used the synergism index to systematically evaluate the city's state of synergism. Li et al. (2012) established a seven-compartment urban metabolic network model of Beijing and used a synergism index to represent the positive and negative utilities for the system as a whole. However, synergism analysis has not yet been applied to analyze the relative utilities for all of the compartments within a system, or to compare the benefits provided to the system by the different types of ecological relationships (e.g., mutualism, competition, and exploitation) among the compartments of the system.

In this paper, we analyze the exchanges of resources and wastes among the compartments of Beijing's metabolic system from 1998 to 2007 using the material-flow accounting method and using a previously established urban metabolic network model based on these flows (Li et al., 2012). Then, we use utility-based ecological network analysis to analyze the degree of synergism of the whole system and of its seven compartments, and define the frequency of the main types of ecological relationships among the compartments. We then examine synergism for each type of relationship and each compartment. On this basis, we describe the utility value obtained by each compartment as a result of belonging to the system. These results identify the type of ecological relationship that contributed most to the system and key components related to compartments that decrease the system's degree of synergism, and can provide theoretical and empirical support for developing policies to promote the healthy development of the urban metabolic system.

2. Methods and data used

2.1. Data used

To quantify the flows within Beijing's urban metabolic network, we adopted the material-flow method. The calculations included the flows for mining, main farm production goods, fertilizer and pesticide use, main industrial products, raw materials, consumer goods, water supply and use, waste discharge and disposal, energy production and consumption, and hidden flows. The raw data for these items were collected from Chinese statistical yearbooks and bulletins published from 1999 to 2008, supplemented by a few values from the research literature. Most of the data were obtained from the China Energy Statistical Yearbook, Beijing Statistical Yearbook, China Statistical Yearbook on the Environment, China Statistical Yearbook on Construction, and the Beijing Water Resources Bulletin. The data sources used in our calculations are summarized in Supplementary Materials (Table S1).

The types of flows analyzed in this study varied considerably and had many different units of measurement, so before it was possible to combine these flows, it was necessary to convert them into consistent units. The original units for the raw data that we used included money (RMB), length (m), area (m^2), volume (m^3), and number (pieces, sets, units, and pairs). We used the conversion factors in Supplementary Materials (Table S2) to convert these flows into units that could be directly compared and integrated, namely mass units (t or kg, depending on the quantity of the flow). For monetary values, we used market prices per unit mass to convert these values into mass units. Because of the short duration of the study period and the low rate of inflation (less than 5% per annum) in China at this time, these calculations did not account for the possible effects of inflation.

2.2. Development of the urban metabolic network model

Details of development of the model used in this study are presented in Li et al. (2012). In summary, the urban metabolic system being modeled represents the socioeconomic system of Beijing, with an emphasis on the industrial (production) and consumption sectors. The system's environment includes the natural environment inside and outside the city's administrative boundary. The environment provides the support required by the socioeconomic system to perform its urban metabolic processes by consuming inputs and producing outputs of materials and energy, as well as by its ability to absorb wastes. Consequently, when we study an urban metabolic system, we must consider the inputs from and outputs to the environment, not just the transformation of materials and energy and their exchanges between internal compartments of the system. However, because the environment is considered to exist outside the system being studied in this model (Zhang et al., 2012), it is not included as one of the system's internal nodes; instead, it is accounted for by establishing separate flow parameters for inputs from and outputs into the environment for each compartment. Table 1 defines the key nodes and the abbreviations that are used in the ecological network model that simulates the urban metabolic system.

The metabolic compartments and processes of an urban metabolic system can be defined using the seven nodes in Table 1, and we can define 16 direct paths between nodes (i.e., not all nodes are directly connected). In addition, we can define six inputs into the system from the environment and six outputs from the system into the environment. Fig. 1 shows the resulting conceptual ecological network model for Beijing's urban metabolic system. By accounting for the flows of materials and energy along each path, we constructed a quantified, weighted network. Based on the availability of sufficiently reliable and detailed data, we have accounted for these flows from 1998 to 2007.We have provided a version of this model in supply chain operations reference (SCOR) model format in Online Supplementary Materials (Fig. S1). In this model, the mining compartment mainly supplies the other compartments by introducing non-living raw materials and energy into the urban metabolic system. After processing and conversion by the materials and energy transformation compartment, these resources can be used for additional processing by the manufacturing and consumption compartments. Agricultural products from the agriculture compartment are supplied to the processing and manufacturing compartment or are consumed directly by the domestic consumption compartment. The wastes emitted by the processing and manufacturing compartments and by the domestic consumption compartment flow to the recycling compartment, and after they are recycled, they can be reused by the processing and manufacturing compartments. Any unused wastes are emitted into the environment.