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Research Paper

Characterizing urban metabolic systems with an ecological hierarchy method, Beijing, China

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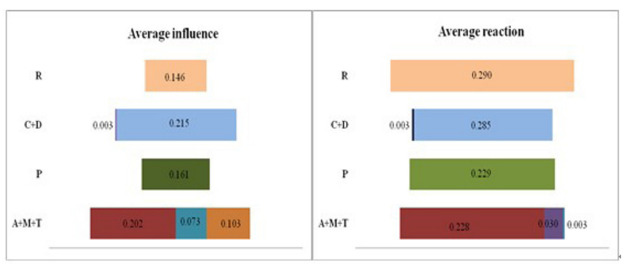
HIGHLIGHTS

- We developed an ecological network model for an urban system.
- We studied Beijing's ecological hierarchy using ecological network analysis.
- The hierarchy's layout was determined by means of utility analysis.
- The top (consumer) level of the hierarchy exerts too much pressure on lower levels.
- The recycling sector must improve its capacity to better support the system.

GRAPHICAL ABSTRACT



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ABSTRACT

The resource and environmental issues that are emerging as a result of rapid urban development have made the study of urban metabolism increasingly important. However, past studies on urban metabolism have focused primarily on the system's external characteristics rather than on the internal production and consumption processes. To better understand the underlying mechanisms of urban metabolic processes, we present a method through which one can examine and characterize the production and consumption flows intrinsic to an urban metabolic system. Drawing upon several analytical procedures from ecological network analysis, we applied the method to a case study in Beijing, China. We collected a large body of statistical data and used it to account for the material flows inside Beijing's system from 1998 to 2007, thereby providing a quantitative network model of the system. We found that the paths between different components of Beijing's urban metabolic system remain simple, that there is insufficient cycling, and that the city's lack of internal environmental support capacity forces it to depend heavily on inputs from the external environment. These results suggest that the city needs to develop the reducer (recycling) component of its hierarchy to reduce the double pressure on its internal environment created by demands for resource supply and for absorption and recycling of wastes and other materials. This will help Beijing to achieve more sustainable development.

1. Introduction

"Metabolism" is a concept that was first developed to describe the flows of energy and materials in biological systems. As this field of research developed, metabolic theory began to be applied in quantitative studies of the exchanges of materials and energy between humans and natural systems (i.e., between ecological and socioeconomic systems), thereby letting researchers quantify the

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scale and composition of a social metabolic system and its relationship with both economic growth and environmental impacts (Anderberg, 1998; Diver, Newman, & Kenworthy, 1996; Fischer-Kowalski, 1997; Huang & Hsu, 2003; Kneese, Ayres, & D'Arge, 1970). The term "urban metabolism" was first used by Burgess (1925), but he did not define the term in sufficient detail nor provide a quantitative basis for subsequent research (Lin, Liu, Luo, Wang, & Zhang, 2012). Later, Wolman (1965) defined urban metabolism in enough detail to provide a framework for research. Subsequent scholars mostly accepted Wolman's opinions, and further interpreted and developed his concept of an urban metabolism (Boyden, Millar, Newcombe, & O'Neill-Canberra, 1981; Brunner, 2007; Duan, 2004; Girardet, 1990; Huang & Hsu, 2003; Kennedy, Cuddihy, & Engel-Yan, 2007; Newman, 1999; Wang, Zhou, Chen, & Liu, 2006; Warren-Rhodes & Koenig, 2001).

Models of urban metabolism have also been continuously developed (Girardet, 1990; Jiang, 2005; Newman, 1999; Zhang, 2013; Zhang, Yang, & Li, 2006; Zhang, Yang, & Yu, 2006, 2009a; Zhou, 2006). Both the urban metabolism recycling model proposed by Girardet (1990) and the system model proposed by Newman (1999) are based on resource inputs and waste outputs, exemplifying typical black-box models. Such models examine the system as a whole without considering its inner workings. Such an approach has been widely applied in case studies of Sydney (Newman, 1999; Newman & Kenworthy, 1999), Tokyo (Hanya & Ambe, 1976), Cape Town (Gasson, 2002), Hong Kong (Boyden et al., 1981; Newcombe, Kalma, & Aston, 1978; Warren-Rhodes & Koenig, 2001), Switzerland's lowland cities (Baccini, 1997), Taipei (Huang, 1998; Huang & Hsu, 2003), Vienna (Hendriks et al., 2000), Paris (Barles, 2007), London (Chartered Institution of Wastes Management, 2002), Toronto (Sahely, Dudding, & Kennedy, 2003), Shenzhen (Yan, Liu, Huang, & Hu, 2003; Zhang & Yang, 2007a, 2007b), Beijing (Zhang & Yang, 2007b; Zhang, Yang, Liu, & Yu, 2011; Zhang et al., 2009a; Zhang, Yang, & Yu, 2009b; Zhang, Zhao, Yang, Chen, & Chen, 2009), and Limerick (Browne, O'Regan, & Moles, 2009). These studies focused their attention on the system's exterior characteristics based on estimates of the total inputs and outputs. Although such research methodologies often include some evaluation of the system's state and related aspects, such as the metabolic fluxes, intensity, and efficiency, they cannot look deeply into the interior of the system to analyze the exchanges of materials and energy among the system's components.

It is difficult to conduct a systematic, in-depth, and quantitative study of the internal production and consumption processes of an urban system because of the complex relationships among the various metabolic activities within the system. Although there are many difficulties in analyzing these internal characteristics of an urban metabolic system, more and more researchers are trying to solve these problems. In designing such studies, several questions must be answered: Which parameter can best represent the differences among a system's internal components? How can we represent the relationships among these components? How can we define the relationships between the components and the system as a whole?

These issues can be studied under the framework of ecological hierarchy theory (Yarrow & Salthe, 2008). The hierarchical structures described by this theory can effectively describe the distribution of the urban metabolic system's components, describe its structure, and analyze the functional relationships among the components within that structure. The theory therefore offers the potential for a breakthrough that provides insights into the interior of the system.

To take advantage of this approach, it is necessary to introduce ecological hierarchy theory into the current models of urban metabolic systems. However, little work has been done on this aspect of urban metabolic research (Zhang, Liu, & Chen, 2012; Zhang, Liu, Li, et al., 2012). To understand the potential benefits of this approach, it is essential to first understand the meaning of hierarchy in such systems.

Hierarchy theory has been widely used to study a variety of complex systems (Yarrow & Salthe, 2008). The generalized form of hierarchy theory includes two connotations: *inclusive* and *progressive* relationships. Inclusive relationships define a component of a system as belonging to the system, and progressive relationships define the flows between the components within the system's hierarchy. Salthe (2001) compared these two kinds of ecological hierarchy, and named them *scalar* and *specification* hierarchies, respectively.

A *scalar* hierarchy describes the relationships between components of a system and the whole system at different scales, and because most ecological hierarchies belong to this type, this type of hierarchy has been widely recognized (Ahl & Allen, 1996; Giampietro, 1994; O'Neill, O'Neill, & Norby, 1991; O'Neill, DeAngelis, Waide, & Allen, 1986; Pattee, 1973; Ratzé, Gillet, Müller, & Stoffel, 2007; Yarrow & Salthe, 2008). The most typical application involves the different research scales that have been used in ecological research, such as the progression from organism to population, community, and ecosystem. Similarly, this hierarchy can be extended in the opposite direction, from organism to cell, molecule, atom, and subatomic particles, or extended beyond the ecosystem to the landscape and biosphere (Salthe, 1991).

A *specification* hierarchy describes the relationships among components at different stages or levels but at the same scale or among the same components but at different scales. Salthe (1991) defined a specification hierarchy as the relationships among different stages of development. However, this description and definition did not account for the fact that components with significant progressive relationships can be found in a system even at the same point in time, or the fact that these relationships can also be expressed by specifications, as in the trophic structure that exists within an ecosystem's food chain or food net. When the specification of a system's hierarchy changes over time, the ecological hierarchy corresponds to the relationships at different stages of development. Table 1 summarizes the differences between scalar and specification hierarchies (Salthe, 1991; Yarrow & Salthe, 2008).

Application of the specification hierarchy is not common in ecosystem research, but is relatively common in the social sciences, especially in the field of philosophy. For example, the progressive relationship from the material world to the world of the mind is one example of such a hierarchical relationship. Odum (1983) proposed the concept of an energy hierarchy, providing a way for specification hierarchical relationships to be used in ecological research. During the next 20 years, Odum systematically defined the basic properties of an energy hierarchy for ecological systems and adopted the energy hierarchy as one of two energy theories that formed the basis for ecological engineering (Odum, 1983; Odum & Odum, 2003).

In the social metabolism field, scalar hierarchies appear in many metabolic systems at many scales, including global, national, provincial, regional, and urban metabolic systems. These metabolic systems are related to each other, and the small-scale metabolic systems combine to create a large-scale system, with each cumulative step representing a higher level in the scalar hierarchy. The collection of metabolic systems of different scales together constitutes a scale hierarchy, and the urban metabolic system is a logical scale for studying the smallest components of larger-scale systems. Within an urban metabolic system, a scale hierarchy also exists between the internal metabolic components (e.g., different economic sectors) and between the units that make up each metabolic component. In this ecological hierarchy, the urban ecosystem (the overall system) is at the top level. However, the system can be subdivided into many metabolic components, and each component