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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