Environmental Pollution 170 (2012) 169–176

Contents lists available at SciVerse ScienceDirect

Environmental Pollution

journal homepage: www.elsevier.com/locate/envpol

Ecological relationship analysis of the urban metabolic system of Beijing, China

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ARTICLE INFO

Article history:
Received 17 February 2012
Received in revised form
4 June 2012
Accepted 1 July 2012

Keywords:
Systematic ecology
Urban metabolism
Ecological networks
Relationship analysis
Utility analysis
Synergism
Beijing

ABSTRACT

Cities can be modelled as giant organisms, with their own metabolic processes, and can therefore be studied using the same tools used for biological metabolic systems. The complicated distribution of compartments within these systems and the functional relationships among them define the system's network structure. Taking Beijing as an example, we divided the city's internal system into metabolic compartments, then used ecological network analysis to calculate a comprehensive utility matrix for the flows between compartments within Beijing's metabolic system from 1998 to 2007 and to identify the corresponding functional relationships among the system's compartments. Our results show how ecological network analysis, utility analysis, and relationship analysis can be used to discover the implied ecological relationships within a metabolic system, thereby providing insights into the system's internal metabolic processes. Such analyses provide scientific support for urban ecological management.

1. Introduction

The concept of an "urban metabolism" was first established by Wolman (1965). His main focus was on the relationships between resources and waste, and he noted that waste output is an inevitable consequence of resource use. As a result, only proper use of resources can reduce the damage to the natural environment caused by waste. Subsequent scholars mostly accepted Wolman's opinion, and built on it to further interpret and develop the concept of urban metabolism (Girardet, 1990; Newman, 1999; Warren-Rhodes and Koenig, 2001; Kennedy et al., 2007; Huang et al., 2006).

As a result of this research, models of urban metabolism have improved continuously (Girardet, 1990; Newman, 1999; Zhang et al., 2009). Using these improved models of urban metabolism, the approach has been widely applied, such as in studies of Hong Kong (Newcombe et al., 1978; Warren-Rhodes and Koenig, 2001), Taipei (Huang and Hsu, 2003), Sydney (Newman, 1999; Newman and Kenworthy, 1999), Vienna (Hendriks et al., 2000), London (Chartered Institution of Wastes Management, 2002), Cape Town (Gasson, 2002), Toronto (Sahely et al., 2003), Shenzhen (Yan et al., 2003; Zhang and Yang, 2007a), Paris (Barles, 2007), and Limerick (Browne et al., 2009). These studies mostly focused on accounting for the components of urban metabolism and evaluating their ecological significance.

Relationship analysis can be used to extend these studies by examining the structural and functional characteristics of a system. However, because of the complex relationships among the various metabolic actors within a city, and an inability to acquire data with sufficiently high resolution, studies of urban metabolisms (Wolman, 1965; Girardet, 1990; Newman, 1999; Warren-Rhodes and Koenig, 2001; Huang and Hsu, 2003; Codoban and Kennedy, 2008; Browne et al., 2009) have not yet achieved a sufficiently detailed analysis of the relationships among the compartments within an urban system. As a result, the research has mainly been based on black-box models that ignore the inner workings of the system, and researchers have instead focused on the system's external characteristics, such as total inputs and outputs. Although this kind of traditional material flow analysis provides some evaluation methods that are useful for revealing a system's overall state, such as metabolic fluxes (Decker et al., 2000; Warren-Rhodes and Koenig, 2001) and metabolic efficiency (Zhang and Yang, 2007a,b; Zhang et al., 2008), it cannot examine the interior of the system and reveal details of the exchanges of materials and energy among the system's compartments. Ecological network analysis can solve this problem by providing a deep understanding of the relationships among these compartments, thereby helping managers to identify constraints and other relationships that may impede urban development.

Ecological network analysis has its roots in the input–output analysis used to study the flows of materials and energy through ecological systems (Fath and Patten, 1999; Schramski et al., 2011). This approach was originally known as "analysis of ecosystem

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0269-7491/$ – see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.envpol.2012.07.010

flows" (Hannon, 1973). In 1976, the first papers on ecological network flow analysis were published (Finn, 1976; Patten et al., 1976). Soon afterwards, general systems theory was added to the approach, especially with the goal of integrating the environment with the models. Finally, ecological network analysis was formally proposed (Patten, 1978).

Ecological network analysis is applied mainly by abstracting the ecosystem into a network of nodes, paths between nodes, and flows along those paths. Integrating this structure within a model makes it possible to analyze the paths and flows related to each node in the network, and this can then provide a systematic and overall view that reflects the structure and function of the system (Fath and Patten, 1999). In recent years, this approach has been widely applied to study natural systems such as bays (Christian and Luczkovich, 1999; Baird et al., 2009), estuaries (Whipple et al., 2007; Christian et al., 2009), saline ponds (Dame and Christian, 2008), near-shore bodies of water such as straits (Jordán et al., 2009), and wetlands (Heymans et al., 2002). It has also been used to study human systems such as cities (Zhang et al., 2009), industries (Bailey et al., 2004a,b; Chen, 2003), fisheries (Walters et al., 1997; Pauly et al., 1998), energy (Zhao, 2006), and utilization of water resources (Bodini and Bondavalli, 2002; Li et al., 2009). However, there have been few studies that used ecological network analysis to study an urban metabolism (e.g., Zhang et al., 2009, 2012).

In this study, we will use Beijing as an example of defining an urban system by dividing the system into different compartments. We then account for the flows of materials and energy along each path in the model of Beijing's urban metabolism using data on these flows from 1998 to 2007. Using the structure of this network, which is derived via ecological relationship analysis, we then performed network utility analysis to focus on the *utility* of the relationships that arise from this structure. By incorporating the economic concept of "utility", ecological network utility analysis can reveal the consequences of the ecological relationships between compartments of the network. By analyzing the trends in the ecological relationships among different nodes, we can also judge whether the overall metabolic system is developing increasing synergism (i.e., increasing net utility) and identify the contradictions and constraints in Beijing's metabolic processes.

2. Methodologies and data sources

2.1. Data sources

Beijing is the political, economic, traffic, and cultural centre of China, and because of its huge population (nearly 20 million people in 2011), the city represents a typical region with extremely centralized and intense human activities. Many resource and environmental problems and conflicts have arisen during the urbanization process for such a large city. The centralization of the population and the large number of processing and manufacturing factories result in a much higher material consumption intensity in Beijing than in smaller cities. Moreover, its resource supply and demand is far from being balanced, which forces the city to rely heavily on imports of resources from outside the system. Heavy resource consumption and inefficient usage of these resources generate large quantities of waste, and exacerbate the imbalance between supply and demand.

To quantify the flows within Beijing's urban metabolic network, we adopted the method of material-flows calculation. The items included in these calculations included mine exploitation, the main farm production goods, fertilizer and pesticide use, the main industrial products, raw materials, consumer goods, water supply and use, pollution and 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 statistical data was 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 Table S1. There are many different types of flows in any system, with many different units of measurement, so before it is possible to combine these flows, they must be converted 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 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. These calculations did not account for the possible effects of inflation.

2.2. Network model

In this paper, the urban metabolic system being modelled represents the socioeconomic system of Beijing, with an emphasis on the industrial and consumption sectors. The system's environment includes the natural environments inside and outside the city's administrative boundary. This 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. 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, it is not included as one of the system's internal nodes; instead, it is accounted for by establishing separate flow parameters for inputs into and outputs from the environment. Table 1 defines the key nodes and the abbreviations that are used in the ecological network model we will develop to simulate 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 into the environment from the system. It is worth noting that there are no inputs from the environment to the materials and energy transformation compartment (T) and no outputs from the construction compartment (C) to the environment. Materials and energy transformation (T) is a sector that produces energy by importing primary products from the energy exploitation or mining compartment (M). Here, we have assumed that raw materials first enter the socioeconomic system through the mining (M) sector and then move to other sectors from this starting point, so there is no direct input from the environment to the materials and energy transformation compartment (T). For the construction sector (C), we assume that its products are immobilized (i.e., they become permanent structures such as buildings) and therefore cannot be involved in the further circulation within the system or output to the environment. A considerable part of the waste from this sector cannot be recycled or reused, and is instead stored within the city. Here, we have assumed that the waste is stored inside the sector itself, and that there is no output from construction (C) to 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 can quantify the network traffic. Based on the availability of sufficiently reliable and detailed data, we have accounted for these flows from 1998 to 2007, a total of 10 years.

2.3. Relationship analysis

In this paper, we used ecological network utility analysis to study the ecological relationships between compartments of the network. Network utility analysis is an

Table 1
Nodes used in the ecological network model of Beijing's urban metabolic system.

Node	Abbrev.	Content
Agriculture	A	Farming, forestry, livestock breeding, and fisheries.
Mining	M	Mining and washing of non-biological original resources such as coal and iron ore; transferring energy resources from the environment to other metabolic compartments.
Processing and manufacturing	P	All primary and advanced processing and manufacturing industries.
Materials and energy transformation	T	Production and distribution of electrical and heating power; exchanges and transformations of energy inside the system.
Construction	C	Construction and demolition of buildings, and other civil engineering.
Recycling	R	Treatment, recycling, and disposal of waste and pollution.
Domestic consumption	D	The consumption of raw and processed materials and energy by the resident population, including sales of goods.