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Evaluation of urban metabolism based on emergy synthesis: A case study for Beijing (China)

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ABSTRACT

Cities ("urban superorganisms") exhibit metabolic processes. Disturbance of these processes results from the high throughput of the socioeconomic system as a result of the flow of resources between it and its surroundings. Based on systematic ecology and emergy synthesis, we developed an emergy-based indicator system for evaluating urban metabolic factors (flux, structures, intensity, efficiency, and density), and evaluated the status of Beijing's environment and economic development by diagramming, accounting for, and analyzing the material, energy, and monetary flows within Beijing's metabolic system using biophysically based ecological accounting. We also compared the results with those of four other Chinese cities (Shanghai, Guangzhou, Ningbo, and Baotou) and China as a whole to assess Beijing's development status. From 1990 to 2004, Beijing's metabolic flux, metabolic intensity, and metabolic density increased significantly. The city's metabolic processes depend excessively on nonrenewable resources, but the pressure on resources from outside of the city decreased continuously. The metabolic efficiency increased by around 12% annually throughout the study period. Beijing had a highest metabolic fluxes and density compared with the four other cities; its metabolic efficiency was lower, and its metabolic intensity was higher. Evaluating these metabolic indicators revealed weaknesses in the urban metabolic system, thereby helping planners to identify measures capable of sustaining these urban metabolic processes.

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1. Introduction

Although metabolism is a purely biological concept, it can be applied by way of analogy to cities because the urban metabolic system is also a mechanism for processing resources and producing wastes. In recent years, ecologists have begun to model hybrid economic and ecological systems such as cities as if they were "superorganisms", with their own metabolic processes. Such research on urban metabolism can contribute to solving urban ecological and environmental problems by highlighting the demands placed by the urban metabolic system on various resources and the pressure of its discharged wastes on the environment (Sahely et al., 2003; Zhang et al., 2006b).

In 1965, Wolman first proposed the concept of urban metabolism (Wolman, 1965; White, 1994). He believed that the operation of the urban system closely resembled a group of related metabolic processes. Later, a number of scholars built on Wolman's ideas by treating cities as if they were organisms, and analyzing the processes and mechanisms that formed their metabolism (Newcombe et al., 1978; Newman, 1999; Fischer-Kowalski, 1998). Other scholars have used this evolving theory to study the metabolisms of Sydney (Newman et al., 1996), Hong Kong (Newcombe et al., 1978), Taiwan (Huang, 1998; Warren-Rhodes and Koenig, 2001), Manchester (Douglas et al., 2002), Shanghai (Zhang et al., 2006a, b), Shenzhen (Yan et al., 2003), Nantong (Yu and Huang, 2005), Paris (Barles, 2007), Toronto (Forkes, 2007), and New York (Kane and Erickson, 2007). Methods of studying urban metabolism include material-flows accounting and energy flows accounting. In the present study, we used emergy analysis, one of the energy accounting methods. The method can bridge the gap between socioeconomic development and protection of the environment that sustains the development (Hall et al., 1986), and can provide a single unit of measurement that accounts for material, energy, and monetary flows within the urban metabolic system and between this metabolic system and its surrounding environment (Odum, 1988).

Emergy is a measure of the real resources supplied by nature to the investigated system (directly or through societal processes), estimated on a common basis, namely that of the biosphere (Odum and Odum, 2001). In emergy analysis, the quality of each form of energy is taken into account by multiplying each flow of energy and matter by its solar transformity (Odum, 1988). Transformity is defined as the quantity of one type of emergy required to generate a unit of energy of another type. Emergy synthesis can quantify

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or place a value on the material, energy, and monetary flows in an urban metabolic system by applying the appropriate transformities. The basic conversion factors for various materials, energies, and products have been modified recently (Brown and Bardi, 2001), so that several conversion factors from older literature have been updated accordingly in our analysis. In our comparison of the published values for various cities, we have omitted the influence of these conversion factors, but it is important to remember that as a result of the changed transformities, the published results and those of our study can only be compared in relative, not absolute, terms.

In this paper, we define the basic characteristics of an urban metabolic system (Zhang et al., 2009a), and determine the flows of energy, materials, and money through this urban metabolism. To account for these flows, we adopted the emergy analysis method (Odum, 1996). Based on this approach, we develop an indicator system for evaluating the urban metabolism based on the city's metabolic processes, and demonstrate the use of this indicator system in a case study of Beijing (China) by analyzing the metabolic fluxes, intensity, efficiency, and pressure in the urban metabolic system.

2. Methodology

2.1. Conceptual model of the urban metabolic system

A city can be conceptualized as a special kind of organism, which means that it embodies certain metabolic processes. These "urban superorganisms" represent urban metabolic systems that extract raw materials from their environment and transform these materials through economic processes. Materials and energy are accumulated for certain periods of time (forming material stocks) and are more or less readily released into the environment as metabolites, such as wastes and emissions (Matthews et al., 2000). The basic metabolic concept has also been extended to include the livability of a city from a human perspective so that the socioeconomic aspects of sustainability are integrated with the environmental aspects (Newman, 1999; Jordan and Vaas, 2000). To simulate a natural metabolic process, a conceptual model of urban metabolic system can be established and used to evaluate the urban superorganism, as shown in Fig. 1.

The urban metabolic system includes both metabolic components (the socioeconomic subsystem) and the internal environment. Here, we consider the internal environment to be the natural regions within the city's administrative boundaries. (For Chinese cities, it is important to note that these boundaries include much more than the built-up area of the city; they also include the surrounding landscape.) The openness and dependence of the urban system mean that the city's metabolic activities cannot be supported solely by the limited urban space within the administrative boundaries, and require support from the city's external environment. The "nutrients" required to sustain the metabolism are continuously transported into the urban system from the external environment; at the same time, the external environment accepts metabolic wastes and other urban metabolites (Zhang et al., 2006a,b). The external environment includes all the regions beyond the city's administrative boundaries that exchange materials and energy with the city.

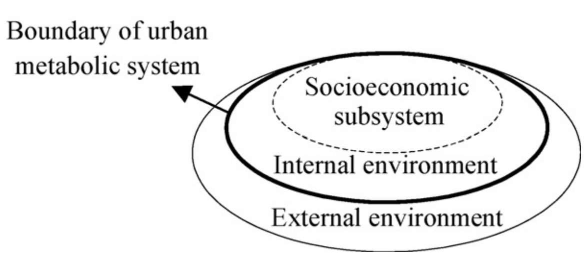

Fig. 1. Illustration of the components of an urban metabolic system. (Note that the "internal environment" includes all natural areas within the city's administrative boundaries.)

2.2. Emergy synthesis

Odum (1996) originated the theory of emergy analysis, and in doing so, introduced two key terms: emergy and transformity. Emergy of one type (usually solar) is defined as the sum of all flows of available energy that are directly and indirectly consumed to make a product, with each of these energies expressed in standardized energy units (usually of the solar type, the solar emjoule, seJ). Odum (1996) described the "available energy" as exergy. When flows are expressed in mass units (e.g., g), the conversion factor is expressed as seJ/g and named specific emergy. Thus, the transformity of a product (τ) equals its emergy divided by the available energy, and the product's emergy can be expressed as

$$E_m = \tau E_x, \quad (1)$$

where E_m is the product's emergy (seJ) and E_x is the available energy or exergy (J) (Odum, 1996). The primary source of energy for all terrestrial ecosystems is sunlight, which drives rain, wind, and most other Earth cycles. In recognition of the importance of solar energy in sustaining most ecosystems, accounting for the varied qualities of energy content inherent in the material and energy flows of an urban system is done by multiplying the energy content or mass of a flow by its solar transformity value, which reflects the energy's qualitative value, thereby obtaining its total solar emergy in solar emjoules (seJ; Huang et al., 2006). During the past three decades, Odum and his colleagues have calculated transformities for a wide range of products and services. Detailed references now allow the calculation of emergy values for most forms of energy and resources (Odum, 1996; Brown and Bardi, 2001; Brown and Ulgiati, 1997, 2004). The larger the transformity, the more solar energy is required to make a product, and the higher its position in the energy hierarchy of the biosphere (Odum, 1988, 1996). Emergy synthesis thus provides an integrated evaluation of the ecological and economic values that flow through a system's metabolism, and makes it possible to study all aspects of urban metabolism in an integrated manner.

Based on the quantification of emergy flows, a series of indices can be calculated by means of emergy synthesis, and the results can be used to evaluate the status of the urban metabolism. In the energy systems diagram of Fig. 2, only the major components and flows that propel the urban metabolic system are described, reflecting the general status of the urban socioeconomic development and eco-environmental quality. To sustain the functions of the urban metabolic system, the basic emergy flows represented by these indices must be ensured. These are the renewable resources emergy (R), nonrenewable resources emergy (N), the resources emergy purchased (imported) from the external environment (IMP), and the resources emergy exported to the external environment (EXP):

$$N = N_0 + N_1 \quad (2)$$

$$IMP = F + G_1 + S_1 \quad (3)$$

$$EXP = G_2 + S_2 \quad (4)$$

Renewable resources emergy (R) mainly includes emergy from sunlight, rain, wind, rivers, and Earth cycles. For an urban metabolic system, R is calculated as the largest inflowing emergy from a renewable source rather than as the sum of all flows, in order to avoid double-counting (Odum et al., 2000). We have also defined

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