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Information indices from ecological network analysis for urban metabolic system

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Abstract

The system analysis of urban metabolic system, still a black box in urban research, has been underlined recently due to its important role in assessing the sustainability of urban ecosystem. An interpretation of the information indices from ecological network analysis when combined with urban metabolic research, however, has not been addressed systematically. In this study, a conceptual network model of urban metabolic systems was developed based on the identification of seven compartments. Emergy analysis and extended exergy analysis were introduced in order to define the proper way of quantifying the material and energy flows within the system. After that, the information indices derived from ecological network analysis such as developmental capacity, ascendancy, overload were proposed as the potential indicators reflecting the sustainability of urban development. An interpretation of these information indices when embedded into urban metabolic system was conducted to further demonstrate their potential application to urban research. With the qualification and interpretation of these information indices from network analysis, this study may provide some lights on unfolding the black box.

Keywords: Urban metabolism; Ecological network analysis; Ascendancy; Overhead.

1. Introduction

When first introduced from biochemistry and physiological ecology, the concept of urban metabolism has been adopted as a fundamental tool in solving the eco-environmental problem caused by urbanization. Many believed that the functioning of urban systems closely resembled the metabolic process in biological systems, or organisms [1-3]. In this sense, the urban metabolism seems to be perfectly modeled as a biosystem quantitatively based on the analysis of resource inputs and waste discharge within the urban system. However, urban metabolic research remains in the black-box stage, mainly due to the lack of methodology quantifying and defining the inherent

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structures and function of urban system.

The system-oriented method, ecological network model, has come into urban ecologists' sights recently with its efficiency and facility in analyzing the structural and functional properties of the system as a whole. Zhang et al. [4] developed a five-compartment network model for urban metabolic system with a case study of four Chinese cities, using emergy to unify all the ecological flows. Liu [5] also accomplished the extended exergy analysis of the urban metabolic function based on network model. Seven compartments, such as extraction, conversion, agriculture, industry, etc., composed his model. Promising as it seems, network analysis was actually controversial in its way to unify eco-flows and the interpretation of analytic indicators. Also, the existing analysis was focused on throughflow analysis and utility analysis, while information indices have not been addressed for urban ecosystem.

This paper attempts to solve these problems with an interpretation of information indices from network analysis into urban metabolic system based on a novel urban metabolic network model.

2. Urban metabolic network model

Urban metabolism is basically an imitation of the metabolic processes in an organism or biosystem. According to the fundamental concept of biochemistry, metabolism is the sum of all chemical processes in an organism, including the adaptation of nutrient from the environment, the transferences of material and energy inside the body and the discharge of wastes into the outside world, like a breathe of body. Many components should be involved and connected in order to maintain the viability and efficiency of the whole body, and therefore making the best use of the improvable material and energy within the environment. Urban metabolic system per se is actually nothing but a huge functional system combined of multiple compartments and numerable material or energy pathways between them. The intake of usable resources from the environment inside and outside urban and the discharge of waste after the ultimate usage of resources represent the behavior or function of urban metabolic system.

Based on the thorough analysis of urban metabolic processes and activities, we constructed a conceptual ecological network model for an urban metabolic system (Fig. 1). This novel model is characterized by seven individual compartments. In this model, compartment 1 (i=1) represents Domestic sector including all the activities of household, government and organization and company; compartment 2 (i=2) represents industry sectors composing mining, construction and electricity; compartment 3 (i=3) stands for agriculture sector encompassing farming, fishery, forestry and food process after the harvest; compartment 4 (i=4) represents the external environment which can provide city the "nutrient" from outside the urban boundary; compartment 5 (i=5) represents internal environment which provides city the "nutrient" and receives the discarded material at the same time within urban boundary; compartment 6 (i=6) stands for tertiary sector including services, distribution of goods and technology; finally, compartment 7 (i=7) stands for transportation of vehicles, travelers and transfer of goods within the urban environment. Herein, we define the internal environment to be the certain regions within the city's administrative boundaries. All the related compartments were identified and considered within the urban boundary except the external environment. When considering the whole material and energy dynamics of urban metabolic system, we define the dynamic boundary to be the area participating in the dynamic processes of urban metabolism, incorporate all the seven compartments described in this model.

The ecological flows between these compartments, which characterize the structure and function of the urban metabolism with the processing of material, energy and currency, may be complex and reticulated. But the flow of all usable resources and energy as a whole was relatively clear after the urban system analysis, the basic route can be described as follows: internal environment-agriculture sector and industry sector-domestic sector, transportation and tertiary sector-external sector. The basic picture of this was also shown in Fig.1.

Multiple roles the components play in urban metabolic system indicate the complicated behaviors and functions for these components. Seven compartments in the established model connect to each other densely with all kinds of eco-flows, including material flow, energy flow and currency flow, etc. These flows contribute to a reticulated form of the urban metabolic system, which means one compartment is relate to other compartments in more than one way, more than one direction. In this model, we have defined 25 metabolic pathways within the dynamic boundary that reflect the exchange of eco-flows among these seven compartments (Fig. 2). Here we denoted f_{ij} as the ecological flow from i compartment to j compartment, and the number of each compartment is consistent with the established conceptual model. All the eco-flows compose an explicit network system of urban, thus facilitate the quantification of the inherent structural and functional attributes.

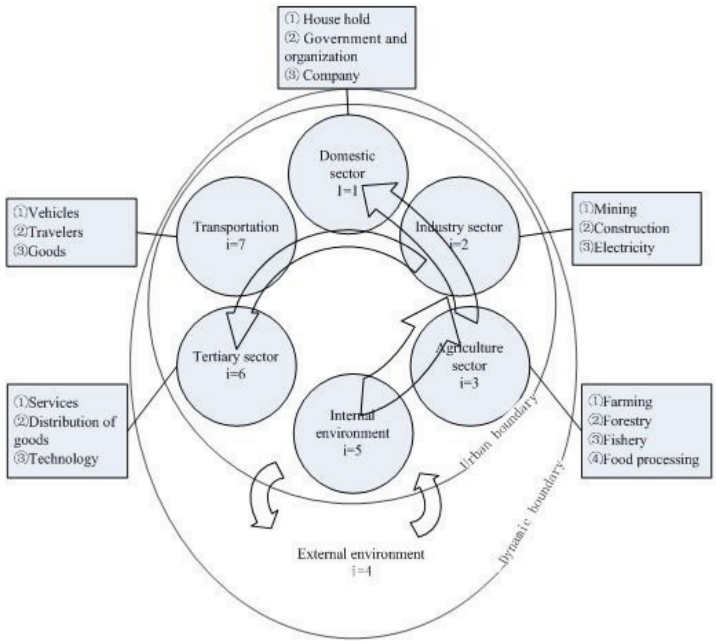

Fig.1 Comprehensive conceptual model of urban metabolic system.

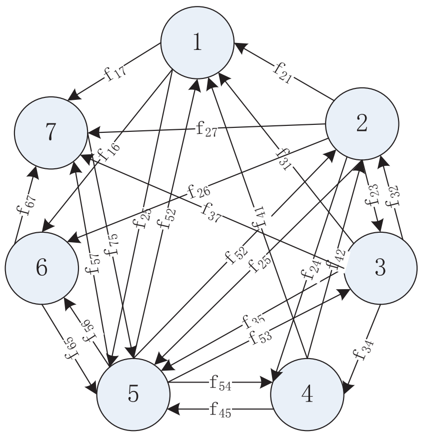

Fig.2 Ecological flows for urban metabolism network model.

3. The unification of eco-flows

Conventionally, a single conservative medium is allowed as to the quantification of ecological flows, for example biomass (e.g., grams of carbon) or energy (e.g., kilojoules), which is the major constraint during network construction. However, more than one kind of flow operates in urban metabolic system. Thus, in order to meet the urgent need of a complete analysis of urban metabolism, ecologists have been focused on applicable methods for a unification of all the eco-flows. Of which, emergy analysis and extended exergy analysis were invented respectively. Emergy analysis was firstly presented by Odum [6] in 1983 to integrate the value of free environment investment, goods, services and information in a common unit of measurement via solar transformity, which makes it possible to evaluate all of the eco-flows (materials, energy, and currency) with urban metabolic system. On the other hand, extended exergy analysis also provides a unified way to measure various flows with solid scientific basis, and provides a wide and clear vision of the use and degradation of resources and energy. These two methods seem to be capable of the unification of eco-flows with its basic rationale, though some arguments on the adaptability into network analysis still exist.

4. The information indices for network analysis

After all these analyses of compartments and eco-flows within the system, many may come to the question about what could be possibly accomplished with such a network. This question legitimately leads to the usable indices of network analysis for urban metabolic system. Zhang et al. made use of throughflow analysis and utility analysis to determine the ecological relationships and mutualism between different compartments in urban system. However, information indices, the newly developed analytical method from information theory, have not been utilized and interpreted yet. As to the network model itself, the inputs to each compartment may not be balanced by its outputs at any particular time [7]. Fortunately, the information indices do not require that components be balanced, this may facilitate the quantification of the structural and functional attributes of urban system which is not in a steady state.

When combined with network analysis, information theory treats compartment as an entity expressing information to other compartments, and pathways as the channel of these information transmission. The message flow and change inherent the system depict how it performs as a whole. It is suggested that the complex structure is the secret of sustainability, and the diversity of processes plays a crucial role in whether a system survives or disappears [8]. Based on AMI and total system throughput (TST), Ulanowicz [9] developed the ascendancy as a measure of the network's potential for competitive advantage over other network configurations. The upper limit to ascendency is the development capacity, and the difference between the capacity and the ascendency is termed as system overhead. According to his theory, development capacity is the whole capacity of the information within the system boundary, which indicates the complexity of the whole system's activities. Ascendancy represents the link-density of the reticulated system, implying the ability of self-organization to direct itself to the mature and fully developed stage. Finally, Overhead indicates the multiplicity of information pathways, which may be closely relate to the buffer ability against perturbances or damages from outside.

Consequently, it is reasonable that the information indices of network analysis be necessarily embedded into the assessment methodology of urban metabolic system, and the interpretation for adjustment be accomplished. In light of Ulanowicz's theory, developing capacity of urban system can be employed as the level or scale of complexity of urban metabolism; ascendancy can be served as the efficiency when processing all the eco-flows in the urban system, in other words, how well the concerned urban has developed as a self-regulate system; while overhead might be possibly recognized as the buffer ability against the disturbance outside the urban boundary (e.g., a sudden shortage of oil supply, or the investment decrease due to policy change) and remain stable, corresponsively. Natural and succinct the interpretation seems, there is no chance for ecologists to avoid the dilemma that an raise of ascendancy is actually at the expense of an decrease of overhead. It then becomes obvious that an exactly perfect balance of the two attributes wound be promising to produces a "healthy" ecosystem, both of operational efficiency and of system stabilizability.

5. Conclusion

Here we develop a conceptual network model for urban network metabolic analysis based on the concept and principal of biosystem's metabolism. The model composes seven compartments (i.e. domestic sector, agriculture sector, industry sector, internal environment, external environment, transportation and tertiary sector), and 25 ecological flows between these compartments. And then two alternative methods of system ecology, emergy analysis and extended exergy analysis, were introduced in quest of a unification of various eco-flows. After that, information indices such as developmental capacity, ascendancy, and overload from ecological network analysis were proposed for an application to urban metabolic research to reflect the sustainability of urban development in terms of system efficiency and stabilizability. More attention should be paid to the balance between ascendancy and overload to account for the best performance of urban metabolic system in the future.

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