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Ecological network analysis of energy metabolism in the Beijing-Tianjin-Hebei (Jing-Jin-Ji) urban agglomeration

Yan Zhang*, Yanxian Li, Hongmei Zheng

State Key Joint Laboratory of Environment Simulation and Pollution Control, School of Environment, Beijing Normal University, Xinjiekouwai Street No. 19, Beijing 100875, China

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ABSTRACT

China's strategy for synergetic development of the Jing-Jin-Ji urban agglomeration is providing a great opportunity for this region. The development of urban agglomeration has promoted energy transmission and transference within the urban system. Therefore, identifying the mechanisms of energy flow processes within the agglomeration is important for integrated and sustainable regional development. Using the concept of "urban metabolism", we constructed an 18-sector network model that represented sectors and energy flow as nodes and pathways, respectively. Next, based on the multi-regional input-output table of China in 2010, we converted monetary values into physical units. Then, by combining these physical units with ecological network analysis, we detailed energy flow processes and calculated energy consumption on sectoral and regional scales. The results showed that the greatest amount of energy was consumed by industry. Beijing was the dominant integrated energy consumer, and most of this energy was consumed by the other services sector. Furthermore, the wholesale and retail sector, and the other services sector in Beijing, and the industry sectors in Tianjin and Hebei, were core sectors in the agglomeration. Tianjin and Hebei were net energy exporters, while Beijing acted as a net importer. This research provides a scientific basis for industrial structure adjustment and optimized energy utilization in the future synergetic development of the agglomeration.

1. Introduction

The Jing-Jin-Ji urban agglomeration (which includes Beijing, Tianjin and Hebei) lies in the Bohai Coastal Region of North China (Fig. 1). In 2014, the synergetic development of the Jing-Jin-Ji region became part of China's national development strategy, and this brought a historical opportunity for the development of the agglomeration. In 2015, the agglomeration, which accounts for 4.56% of the total national urban area, 1/8 of the national population and 1/10 of the national economy, had become one of the three economic growth poles in China (Tianjin Economic Research Group, 2014). The energy consumption of the Jing-Jin-Ji agglomeration accounts for a high percentage of the total energy consumption of China (10.36%; 443 million tons coal equivalent (Mtce). Coal is currently the main energy source in this region, and coal usage in the Jing-Jin-Ji agglomeration accounted for 67.01% of the national coal consumption in 2013 (Xiao and Wei, 2015). The geographic locations of cities promote the formation of close connections (Qu et al., 2013; Zhang et al., 2016). For example, research has indicated that 8.9% and 12.2% of energy used in Beijing and Tianjin, respectively, is supplied by Hebei Province (Zhang et al., 2015a). Such connections provide a favorable platform for energy transmission and transference, as well as the exchange of products and services within the urban agglomeration. Therefore, it has become urgent to explore regional and sectoral energy consumption, energy exchange, and the influence of these energy transmissions and transferences within the agglomeration (Li et al., 2014; Zhang et al., 2015b). Because studying energy transmission and transference from a metabolic perspective is of great significance, we introduced the concept of "urban metabolism". Treating the urban agglomeration as an organism, we analyzed the processes and mechanisms of urban energy metabolism to identify vital nodes and pivotal pathways, further to support the coordination of regional development and optimize regional energy utilization.

The concept of urban agglomeration metabolism was developed on the basis of urban metabolism. When Wolman (1965) first proposed the concept of urban metabolism, he regarded a city as a complete ecosystem, and proposed that metabolism is the process by which materials and energy are inputted, and products and wastes are outputted from the system. After Wolman, many scholars thoroughly discussed and extended this theory and the application of urban metabolism. Focusing on the metabolic flow of

* Corresponding author.
E-mail address: zhangyanyxy@126.com (Y. Zhang).

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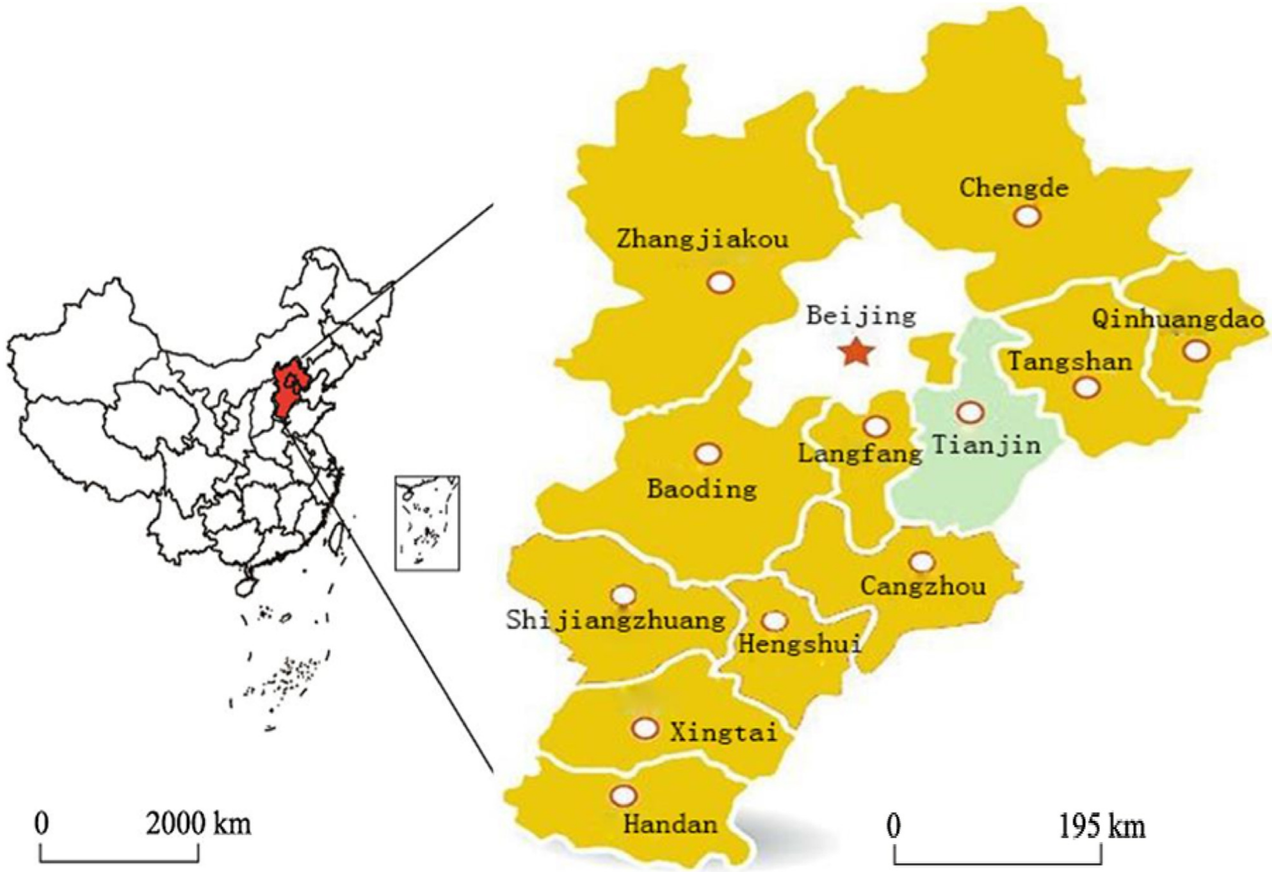

Fig. 1. The location and regions of the Beijing-Tianjin-Hebei (Jing-Jin-Ji) urban agglomeration.

water (Kennedy et al., 2007; Baker, 2009; Tambo, 2002; Zhang et al., 2010a, 2010b), food (Bohle, 1994; Forkes, 2007), energy (Zucchetto, 1975; Huang, 1998; Zhang et al., 2009; Ngo and Pataki, 2008; Pincetl et al., 2012) and waste (Decker et al., 2000; Liang and Zhang, 2012; Qu et al., 2013), these researchers have explored the mechanism of urban metabolism by material flow and energy flow analyses, thus identifying the eco-environmental and energy problems caused by urbanization (Chen et al., 2010). These studies provide effective tools and measures for understanding sustainable urban development.

Vast amounts of energy are normally used for the maintenance of the structure and function of urban systems during the energy flow process (Liu et al., 2011). Urban energy metabolism is an important part of the study of urban metabolism. Some scholars have calculated the energy consumption of cities such as Miami (Zucchetto, 1975), Los Angeles (Ngo and Pataki, 2008), Hong Kong (Newcombe et al., 1978), Taipei (Huang, 1998), an Irish city region (Browne et al., 2012), and Beijing (Chen and Chen, 2015); some have used the emergy theory to quantify the overall fluxes of energy and other substances in Beijing (Zhang et al., 2009) and Toronto (Halla et al., 2003) by measuring energy and obtaining information about metabolic flow; others have investigated urban systems such as Beijing (Zhang et al., 2011a) and the Jing-Jin-Ji urban agglomeration (Zhang et al., 2015b; Wang and Chen, 2016) by analyzing the mechanism of the urban energy metabolism process to further understand the structure and function of the urban system.

At present, the concept of urban energy metabolism is not just limited to tangible energy (e.g., the flow of oil and electricity). Many scholars also include the intangible energy (e.g., energy flow embodied in the exchange of services and products) that is used in regions or sectors within the urban system (Zhang et al., 2016). Therefore, attention should be paid to the energy consumption of intermediate products and services as well as final goods when studying urban energy metabolism. The sum of this energy consumption is the total energy embodied in all urban metabolic processes, including upstream activities (Treloar, 1997). Input-output analysis is an effective method of accounting for embodied energy (Baynes et al., 2011; Zhang et al., 2013a, 2013b; Zhang et al., 2015b). There are usually regional and sectoral discrepancies in the use of products and services because of different production structures and technology, and cities also have different metabolic patterns and characteristics. Thus, to eliminate the influence of disparities in the magnitude of the energy embodied in the input flow and output flow (Wiedmann, 2009; Zhang et al., 2016), the multi-regional input-output analysis was introduced to study embodied energy transmission and transference (Zhang et al., 2013a, 2013b), and the energy consumption embodied in various economic activities was quantitatively analyzed on global (Chen and Chen, 2010), national (Cui et al., 2015) and regional scales (Liang et al., 2007; Zhang et al., 2014a, 2014b; Zhang et al., 2015b, 2015c). When we study the energy flow of an urban system using the existing input-output analysis, in addition to the energy consumed through one path length among sectors, the indirect flow resulting from multiple paths should also be deeply analyzed (Zhang et al., 2016). Consequently, this provides the possibility of introducing network analysis, thus establishing relevant network models of urban metabolic systems from the perspective of system ecology.

Currently, ecological network analysis has been applied in the study of urban metabolism, and it imitates the process of urban material and energy flow by constructing network models (Baird et al., 2008; Li et al., 2009; Lu et al., 2014), hence to facilitate the development of urban energy utilization and the adjustment of