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Multi-scale analysis of the energy metabolic processes in the Beijing–Tianjin–Hebei (Jing-Jin-Ji) urban agglomeration

Yan Hao, Menghui Zhang, Yan Zhang*, Chenling Fu, Zhongming Lu

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

The area of the Beijing–Tianjin–Hebei (Jing-Jin-Ji) region is about 2.25% of China land area. But the energy consumption and carbon emission of Jing-Jin-Ji region account for more than 10% of China's total consumption and emissions. To reduce the region's energy consumption and carbon emission, we studied energy flow process in this region. The previous research on energy flow is concentrated on a single scale, with little multi-scale integration. In this study, based on framework of urban metabolism, we used ecological network analysis method to study the region's energy metabolism and ecological relationship among nodes at two scales: in 3-node and 13-node models of the agglomeration. The integral (direct + indirect) energy consumption in the 3-node model first increased, then decreased, from 2002 to 2010; consumption in the 13-node model first decreased, then increased. The direct and integral energy flows showed that Hebei provided the most energy to Beijing in the 3-node network; in the 13-node network, Tangshan provided the most energy to the other 12 cities. In terms of the ecological relationships among the nodes, the 13-node model showed proportionally more competition relationships than the 3-node model. The relationships among Beijing, Tianjin, and Hebei were dominated by exploitation and control. Based on the analysis of flow and relationship, the importance of multi-scale model research is verified, which serves different research objectives and helps researchers choose the appropriate scale model under different data acquisition precision and research depth.

1. Introduction

As urbanization and industrialization progress, urban agglomerations develop and become core areas for the economy and the environment. China's Beijing–Tianjin–Hebei (Jing-Jin-Ji) urban agglomeration is one of the world's largest, and has therefore attracted much attention from researchers and government managers. However, as the industrial structures of Beijing, Tianjin, and Hebei are similar, the potential for synergies was low, and the region's ecological capacity was limited, leading to high ecological and environmental costs and excessively high consumption of energy. In 2013, energy consumption in the Jing-Jin-Ji region was 44.27×10^6 tce (tonnes coal equivalent), and accounted for 10.4% of China's energy consumption. However, energy consumption analyses for urban agglomerations should account for more than just the total consumption; they should also identify the provinces or cities that are most responsible for this total. Four cities together consumed more than half of this total: 18.5% for Baoding, 16.7% for Beijing, 16.5% for Tangshan, and 12.5% for Handan (Du et al., 2016). This kind of analysis reveals the key locations of energy consumption so that government managers can focus on these locations in an effort to reduce energy consumption and pollutant emission.

Once these key locations are known, it becomes possible to trace the flows of energy among them and use a range of techniques to improve our understanding of these flows. Such an analysis can be conducted at a range of scales for a key agglomeration such as the Jing-Jin-Ji region. From an administrative perspective, Hebei is a province, whereas Beijing and Tianjin are referred to as "provincial-scale municipalities" because in importance, they are equivalent to provinces (For simplicity, we will refer to Beijing and Tianjin as provinces hereafter.). In addition, Hebei contains several large cities, and can thus be subdivided. Different insights will be obtained from analyzing energy flows at different scales. In the present study, we demonstrate the effects of scale by treating the Jing-Jin-Ji region as a single node, then separating it into three nodes (Beijing, Tianjin, and Hebei) and 13 nodes (Beijing, Tianjin, and 11 cities within Hebei). One advantage of this increasing resolution is that it allows us to trace more than just direct flows; we can also account for indirect flows that pass through one or more intermediate nodes before arriving at the flow's final destination. This

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* Corresponding author.
E-mail address: yzhang@bnu.edu.cn (Y. Zhang).

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approach permits a more comprehensive evaluation of the current status of an urban agglomeration, making it possible to develop solutions that will optimize energy use and conservation.

Research on energy flows through an urban agglomeration developed from older research on urban metabolism. This research is based on a metaphor in which flows of resources and wastes among regions of the agglomeration can be considered analogous to the metabolic flows in a living organism. The concept of an urban metabolism was proposed by Wolman (1965), who proposed the concept as a way to analyze the material or energy flows within a single city. Until recently, the boundary of the urban metabolic system remained restricted to a single city, where the approach allowed researchers to trace the flows of resources and wastes within that city and between the city and its surrounding environment (Hashimoto and Moriguchi, 2004; Liang and Zhang, 2011; Liang et al., 2013; Zhang et al., 2012).

However, in practice, cities are open systems that frequently exchange materials and energy with other cities. Based on this recognition, urban metabolic analysis has been extended to both networks of independent cities and to urban agglomerations, and the boundaries include both the cities and the surrounding rural areas that provide food, energy, or other resources (Billen et al., 2012). Barles (2009) studied both the urban area of Paris and its surroundings, and found that the urban area depended strongly on resource inputs from areas outside the city, and also emitted wastes to these areas. Nonetheless, the overall metropolitan area, which included rural areas, was largely able to sustain itself. Billen et al. (2012) studied 11 European cities, including Paris, London, and Brussels, to analyze the interaction between the cities and their surrounding areas from the perspectives of flows of energy, food, and water. They found strong interdependence between a city and its surrounding areas. Poruschi (2013) also showed that extending the research boundary beyond that of the city (to southeastern Queensland, Australia) and considering the external environment provided a more robust framework for economic and environmental analysis to support plans for sustainable regional development. Kennedy et al. (2014) pointed out that the choice of system boundaries strongly influenced the results of such analyses.

Other researchers have focused on urban agglomerations, which represent groups of cities that are close together and that are strongly socially or economically connected. This permits analyses both at the level of the overall agglomeration and at the level of individual cities. Baynes and Bai (2012) studied direct energy consumption for the metropolitan area of Melbourne, Australia. Zhang et al. (2016a,b) studied embodied energy flows in the Jing-Jin-Ji agglomeration. Marteleira et al. (2014) studied water metabolism and recycling for the metropolitan area of Lisbon, Portugal. Baker et al. (2007) studied the transformations of carbon, nitrogen, and phosphorus in the Minneapolis–St. Paul, United States, metropolitan area. Heinonen and Junnila (2011) studied the carbon metabolism of Helsinki and Porvoo, Finland. Nixon and Fulweiler (2012) studied the nitrogen and phosphorus metabolism of Narragansett Bay, United States. Analyses can also focus on combinations of flows (Swaney et al., 2012; Pincetl et al., 2014; Wang and Chen, 2016) and environmental impacts (González et al., 2013; Moore et al., 2013; Garcia-Montiel et al., 2014; Zhang et al., 2016a,b).

Furthermore, the analysis can be spatially explicit. For example, Lee et al. (2009) combined an analysis of land use and cover types with resource consumption data to identify the resource utilization level of different land uses, and several researchers have compared metropolitan areas (Heinonen and Junnila, 2011; Kennedy et al., 2011; Rosado et al., 2014). Such studies can also be conducted at a range of scales. For example, some Chinese scholars have studied metabolic processes at a provincial scale, such as the social metabolism of Liaoning Province (Xu et al., 2008), and the carbon metabolisms of Jiangsu Province (Liang and Zhang, 2011) and of Hubei Province (Yang et al., 2015a). Therefore, choosing an urban agglomeration as a case study to analyze the interaction among cities at a range of scales seems likely to provide important insights.

To perform such analyses, it's first necessary to identify and quantify the flows of energy and materials. Input-output analysis is commonly used to quantify the interactions among industries. It is based on tracing the direct and indirect resource consumption or emission of wastes embodied in consumption processes (Leontief, 1970; Miller and Blair, 2009). To differentiate the impacts of the technologies used to produce primary and intermediate products, multi-regional input-output tables can be established and used to analyze the resource flows among regions and among the sectors in a given region (Zhang et al., 2013). This method is an effective way to trace industrial chains by quantifying the interactions among sectors caused by the resource consumption activities (Wiedmann, 2009; Wiedmann et al., 2007). This method was first used to analyze the economic linkages among sectors in Italy and the United States at a national scale (Polenske, 1980). Subsequently, the method was extended to analyze virtual water and water footprints (Feng and Hubacek, 2015; Feng et al., 2012, 2014; Jiang et al., 2015; Wang et al., 2014; Yang et al., 2012; Zhang and Anadon, 2014); the impacts of global trade on biodiversity (Lenzen et al., 2012); emission of wastes such as greenhouse gases (Yu et al., 2013), carbon dioxide (Zhang and Tang, 2015), SO_2 (Prell et al., 2014), fine particulate matter (Lin et al., 2014), and total suspended particulate matter (Yang et al., 2015b); carbon emission (Tian et al., 2014); material footprints (Wiedmann et al., 2015); agricultural products (Kastner et al., 2011); ecological footprints (Zhou and Imura, 2011); energy consumption (Liang et al., 2007; Zhang et al., 2013); and the ecological footprints of multiple materials (Galli et al., 2012).

However, further insights could be gained from these flows of energy and materials. For example, it is necessary to study the functional attributes of the components of an urban agglomeration. Ecological network analysis, when combined with multi-regional input-output analysis, can provide important insights into the structural and functional attributes of whole systems or of specific sectors within a system. Zhang et al. (2015a) analyzed the energy consumption structure of 28 sectors in Beijing from the carbon footprint perspective. Chen and Chen (2015) compared analyses based on material flows, input-output analysis, and ecological network analysis, and showed that ecological network analysis provided the clearest insights into the interactions among sectors. However, each of these approaches provides complementary insights, so combining them can produce a more comprehensive understanding of complex systems such as an urban agglomeration system. At a regional scale, Zhang et al. (2015b) studied the energy metabolic processes of China's 30 provinces, and Zhang et al. (2016c) examined these processes for the sectors in single or multiple regions of the Jing-Jin-Ji urban agglomeration to identify the key actors in different sectors.

In the present study, we used urban metabolism theory to trace the energy flows at three scales in the Jing-Jin-Ji agglomeration: as a single node for the whole region, as three nodes (Beijing, Tianjin, and Hebei), and as 13 nodes (individual cities within the agglomeration). The results fill gaps in our data on this large and complex urban agglomeration, and in contrast with previous research, provided additional insights into the effects of scale on such analyses. By abstracting these components of the overall agglomeration into networks, we were able to use ecological network analysis to analyze the flows among the components of the system and define their functional and ecological relationships. Our goals were to provide insights at different network scales, ranging from 1 to 13 nodes, to identify the functional ecological attributes of the system components and identify the nodes with the highest energy