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Spatial variation in the ecological relationships among the components of Beijing's carbon metabolic system

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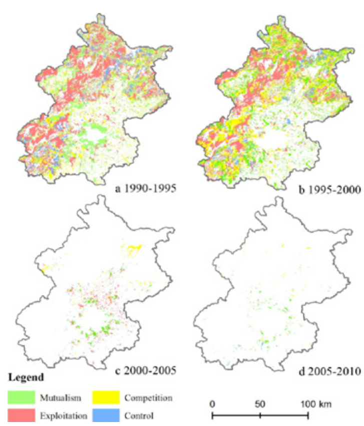
HIGHLIGHTS

- We developed a spatially explicit urban carbon metabolic network model.
- The model accounted for both socioeconomic and natural (environmental) components.
- Mutualism was too infrequent, and was easily disturbed by urban expansion.
- Increasing competition relationships led to an unbalanced carbon metabolism.
- Transportation and industrial was the main component that exploited others.

GRAPHICAL ABSTRACT



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ABSTRACT

In this paper, we construct a spatially explicit model of carbon metabolism for the flows of carbon among the components of an urban area. We used the model to identify spatial heterogeneity in the ecological relationships within a carbon metabolic network. We combined land-use and cover type maps for Beijing from 1990 to 2010 with empirical coefficients and socioeconomic data to quantify the flows. We used utility analysis to determine the ecological relationships between the components of the system and analyzed their changes during urban development. We used ArcGIS to analyze their spatial variation. We found that the positive utilities in Beijing decreased over time and that negative relationships mostly outweighed positive relationships after 2000. The main ecological relationships were distributed throughout the entire urban area before 2000; subsequently, exploitation, control, and mutualism relationships became concentrated in the southeast, leaving competition relationships to dominate the northwest. Mutualism relationships were most common for natural components, but were not stable because they were easily disturbed by urban expansion. Transportation and industrial land and urban land were the most important contributors to exploitation and control relationships and may be important indicators of spatial adjustment. Increasing competition relationships unbalanced the carbon metabolism, and limitations on the area of land available for development and on the water resources led to increasingly serious competition. The results provide an objective basis for planning adjustments to Beijing's land-use patterns to improve its carbon metabolism and reduce carbon emission.

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1. Introduction

Urban areas contribute around 75% of the total global carbon dioxide emissions (IPCC, 2007); among this, one-third of urban carbon emissions results from land-use and cover changes (Denman et al., 2007). An urban area is a complex network that contains diverse social, economic, and natural activities. A wide range of material and energy exchanges exist within and between the sectors affected by these activities. These exchanges, analogous to the flows in biological metabolism, compose the metabolic processes in an urban system. Uncontrolled urban development has strong negative effects on the environment and disturbs these metabolic processes (Zhang et al., 2012), thereby creating a disorderly distribution of land-use and cover types in the city (López et al., 2001). Beijing, as a capital city, provides a good example undergoing rapid growth and development. From 1992 to 2008, urban sprawl resulted in Beijing converting 20% of cultivated land into constructed land. During the same period, 28% of the forested land was converted to constructed land (Miao et al., 2011). Since 2008, only 2.4% of the carbon emissions from Beijing have been offset by carbon sequestration within the city (Zhang et al., 2014).

As the source and target of all activities that produce carbon emissions and sequestration, a city's land-use and cover types have complex and mixed relationships. The rapid alteration of cities also accelerates these relationships and their changes over time. In the present study, we aim to understand the nature of the relationships among a city's components and analyze the spatial variation of these relationships over time. The results can help to construct an effective and harmonious urban ecological network that improves the overall urban metabolism.

Wolman (1965) defined the concept of urban metabolism by describing a city as analogous to an ecosystem. He outlined how materials, energy, food, and other inputs flowed into the system, and how the system generated products and wastes. Thus far, scholars have mainly focused on the flows of a single currency or element in urban metabolism studies, such as water (Tambo, 2002; Zhang et al., 2010), nitrogen (Forkes, 2007; Saikku et al., 2007), and carbon (Kennedy et al., 2009, 2010). In the studies of urban carbon flows, carbon emission from socioeconomic activities was soon identified as a concern. Carbon flows have therefore been the target of urban materials accounting for decades (e.g., Ayres and Kneese, 1969). Based on this research, researchers have developed a series of carbon budget systems, such as the accounting system from the International Council for Local Environmental Initiatives (www.iclei.org), which mainly focuses on energy and waste emissions, and the widely used carbon emission coefficients proposed by the Intergovernmental Panel on Climate Change (IPCC; www.ipcc-nggip.iges.or.jp/EFDB/main.php).

As studies of urban metabolism increased in depth, scholars increasingly recognized that forests and other types of urban green space within cities were key components of the urban carbon balance (Liu and Li, 2012; Zhao et al., 2010). For example, some scholars focused on the changes in carbon stocks caused by land-use and cover changes when they considered the carbon metabolism of urban areas (Christen et al., 2010; Svirejeva-Hopkins and Schellnhuber, 2006). Exploring the carbon flows through an entire urban ecosystem by taking advantage of the insights provided by urban metabolism research can provide a more robust framework for understanding these flows (Pataki et al., 2006). Because of the ongoing application of urban metabolism theory in management and design research (Kennedy et al., 2010, 2011), researchers have begun to account for the urban carbon metabolism during urban planning, with the goal of reducing carbon emissions. Meanwhile, studies of the interactions between carbon metabolism and land-use and cover types have increased the spatial resolution of the analysis (Huang and Chen, 2009; Marull et al., 2010), and have thereby made it possible to analyze the spatial variation in urban metabolic processes (Zhang et al., 2014). These studies have provided the basis for building increasingly accurate and useful spatial models of carbon metabolic networks and for quantitatively analyzing the ecological relationships among the components of these networks.

Ecological network analysis originated in the economic analysis of monetary flows, and examines the exchanges of materials (i.e., inputs and outputs) between a given component of a system and adjacent components. Patten (1982) further refined the method to examine the interdependencies among the components of an ecosystem by describing the flows of materials and energy, and first applied network utility analysis using flow matrices to explain the relative gains and losses within interactive networks (Patten, 1991). Network utility analysis, based on a close examination of the pairs of objects linked by a flow, analyzes the ecological system integrally to reveal the nature of the interactions between pairs of components. The use of network utility analysis to determine community-level relationships has important practical applications (Fath, 2007).

Ecological network analysis can be used to analyze a system's inherent structure and functional properties. Scholars systematically described the network construction and provided a range of methods for quantitatively exploring the properties of the network (Ulanowicz, 2004), for example synergism, ascendency, and system cycling (Fath and Patten, 1999; Huang and Ulanowicz, 2014). Some software can be helpful for the implementation of ecological network analysis. Ulanowicz (2004) and Schramski et al. (2011) introduced NETWRK, ECOPATH and EcoNet in their studies which can quantitatively evaluate the properties of network. The R package provided by Borrett and Lau (2014) and the MATLAB function provided by Fath and Borrett (2006) can also provide fast and accurate computations.

This approach has become increasingly important in system design and analysis and widely used to study the flows within natural ecosystems (Hines et al., 2015; Small et al., 2014). Some researchers have further applied the approach to the studies of socioeconomic systems (Goerner et al., 2009; Huang and Ulanowicz, 2014), and analyzed the structure and function of an urban metabolic network. For example, Chen and Chen (2012a, 2012b) built a carbon network model based on network environ analysis. The authors focused on the carbon transitions embodied in the products of socioeconomic activities, and included a consideration of natural activities as a component within the overall system. Furthermore, urban development plans supported by network environ analysis have not been implemented with a spatial specific focus because of a lack of a spatially explicit expression.

In the present study, we examine the effects of land-use and cover change on carbon transition processes within an urban network, as these transitions are an important part of the urban metabolism. To perform this analysis, we developed a spatially explicit carbon flux network model to link the natural and socioeconomic components of an urban ecosystem based on their roles in the city's carbon metabolism. Moreover, the network model focuses more on the system's natural and socioeconomic features. To make the process more concrete, we chose Beijing, China's capital, as a case study, and determined the ecological relationships among the components of Beijing's metabolic system from 1990 to 2010. Then we analyzed the model's embodied ecological relationships, their spatial variations and changes over time, and their contribution to each component and the temporal trends between adjacent periods.

2. Methodologies

2.1. The spatially explicit urban carbon metabolic network model

Land-use and cover change processes cause exchanges of carbon metabolic capacity between landscape components and between these components and their external environment (here, the atmosphere) in the form of input flows (z) and output flows (y). In the present study, we have focused on land-use and cover change, so the flows represent transformations of an area with one land-use or cover type to a different type; this is equivalent to a change in the