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Development of a spatially explicit network model of urban metabolism and analysis of the distribution of ecological relationships: case study of Beijing, China

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ABSTRACT

In this paper, we develop a spatially explicit model of carbon transfers between regions of an urban area. The carbon transfers represent the metabolic processes due to regional land use changes. We used the model to identify spatial heterogeneity in the carbon metabolic structure, functions, and relationships within the network. Data for Beijing from 1990, 1995, 2000, 2005, and 2010, were combined with empirical coefficients, to construct the network. We used ecological network analysis to analyze the structure and function of the network, and to determine the ecological relationships between the components of the system, their distribution, and their changes over time. The analysis revealed that carbon throughflow of the network decreased and positive relations mostly outweighed negative relations. Exploitation relationships were the dominant type in Beijing during most of the study period, particularly in the northwest before 2000, but moved towards the southeast over time, leaving competition relationships with losses of benefits dominant in the northwest. Mutualism relationships with mainly beneficial carbon flows were dominant in the southeast, increasing in frequency in this region throughout the study period. The results provide a theoretical basis for planning adjustments to the city's structure to achieve low-carbon goals.

1. Introduction

Land use and cover change (LUCC) accounts for one-third of urban carbon emissions (Denman et al., 2007), and because carbon sequestration is closely related to the presence of natural land cover (Houghton, 2003), the balance between carbon emission and sequestration depends on how much natural land is converted to human uses. In addition to the inputs (carbon sequestration) and outputs (carbon emission) between land systems and the atmosphere, carbon transitions occur between socioeconomic systems and the environment. Within a mixed natural and socioeconomic system, these transitions are also directly related to LUCC. For instance, in the United States carbon storage in vegetation generally increases by 0.02 PgC yr^{-1} when constructed land (land that has been converted into buildings, roads, and other forms of infrastructure) is transformed into farmland (Imhoff et al., 2004). Similarly, transforming forests near Seattle, Washington into constructed land decreased carbon storage in vegetation by 1.2 Mg C ha^{-1} yr^{-1} (Hutyra et al., 2011).

LUCC occurs within developing cities, and can have important effects on a city's carbon balance as the distribution of various land use and cover types change. For example, land uses and cover types in Beijing exhibit strong spatial and temporal variation leading to frequent carbon transition processes. From 1992 to 2008, urban sprawl in Beijing converted 792.7 km^2 of cultivated land (20% of the total arable land area in 1990) into constructed land. During the same period, 28% of the forested land was converted to constructed land (Miao et al., 2011). This imbalance caused by construction has led to increasingly significant environmental contradictions in Beijing (Beijng Municipal Bureau of Land and Resources, 2010).

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Urban planners must construct an effective and harmonious urban ecological network and a sustainable urban development environment (Zhang and Wang, 2006). As part of the goal of reducing carbon emissions, this paper aimed to identify the key control points required for implementing quantitative adjustments to the overall regional development to improve its carbon balance.

Wolman (1965) defined the concept of urban metabolism by describing the city as analogous to an ecosystem. He outlined how materials, energy, food, and other inputs flowed into the system, and how products and wastes are generated by the system. Urban metabolism is a process of resource consumption and waste generation, and accounts for the circulation, emissions, disposal, and use of resources and wastes by the city (Zhang, 2013). Tracking the flow of materials and energy through an entire urban ecosystem can provide a more robust framework for understanding these flows (Pataki et al., 2006). Some scholars have studied key flows of a single material or element within an urban metabolism, such as water (Tambo, 2002; Zhang et al., 2010), energy (Huang, 1998; Zhang et al., 2011), copper (Gordon et al., 2006; Tanimoto et al., 2010), and nitrogen (Forkes, 2007; Saikku et al., 2007). With growing concern about climate change, scholars have adopted the concept to study the urban carbon metabolism (Sovacool and Brown, 2009; Karakiewicz, 2011). Some scholars have focused on the flow of carbon emissions from cities into the atmosphere, and have focused on carbon emissions produced by socioeconomic activities, such as energy and resource consumption by the transportation infrastructure and electricity use (Kennedy et al., 2010, 2011). Others have studied carbon emissions associated with specific economic activities, such as those produced by transportation in a port city (Villalba and Gemechu, 2011) or by residential energy consumption (Ye et al., 2011).

Some scholars have focused on carbon emissions in socioeconomic activities and natural carbon sequestration from the atmosphere by the biosphere. Baccini (1996) considered carbon emissions produced by urban socioeconomic activities, while accounting for agricultural activities, and further focused on carbon sequestration by farmland and forest. Others have focused on carbon transitions embodied in the products of socioeconomic activities, including a consideration of natural activities as a component of the overall system but ignoring the carbon metabolic processes in the natural activities (Chen and Chen, 2012a,b). After ongoing application of urban metabolism in management and design research (Huang et al., 2006; Kennedy et al., 2011), researchers began to study the correlations between an urban metabolism and the spatial distribution of land use within the urban area (Huang and Chen, 2009; Marull et al., 2010). Pauleit and Duhme (2000) studied the interactions between carbon emissions and land use. Christen et al. (2010) focused on the changes in carbon stocks caused by LUCC. Others have looked at the increases in carbon storage caused by transforming cultivated land into woodland and grassland (Dixon et al., 1994), and the decreases in carbon storage caused by the reverse transformation (Houghton and Goodale, 2004). Some studies calculated the carbon flows based on urban metabolism and evaluated the impact of urban form on the pattern of carbon emission and sequestration. Researchers conducted the studies in several European cities like London and Florence and showed that different urban form affected the distribution of carbon flows significantly (Blecic et al., 2014; Chrysoulakis et al., 2010, 2013). These studies have provided the basis for a fuller consideration of carbon transition processes, which is the key to building an accurate and useful spatial model of the network's carbon metabolism.

Such a carbon flux model has been built based on network environ analysis (Chen and Chen, 2012a,b), which is a form of ecological network analysis (ENA). ENA originated in the economic analysis of monetary flows and examines the exchanges of materials (i.e., inputs and outputs) between one component of a system and adjacent components. Hannon (1973) first applied economic input–output analysis (the Leontief model) to simulate the structural distribution of ecosystem components and the interrelationships among trophic levels. Finn (1976) improved the method and Patten (1982) further refined the method to examine the interdependencies among the components of an ecosystem by describing the flows of materials and energy. This approach establishes a network flow diagram that captures both direct and indirect flows of materials and energy among the components of a system (Levine, 1980; Patten, 1982).

Network environ analysis reveals the function and interdependencies within a system (Fath and Killian, 2007; Patten, 1982). This approach has been widely used to study the flows within natural ecosystems and socioeconomic systems (Finn, 1976; Baird et al., 2009; Zhang et al., 2010; Li et al., 2012). However, such studies provide insufficient consideration of the relationships between the natural components of the system. And, because they lacked a spatially explicit expression, urban development plans supported by a network environ analysis could not be implemented with a spatially specific focus. To solve this problem, some models have adopted the perspective of landscape ecology to reflect the interactions created by spatial relationships within an environmental landscape. The idea of landscape networks originated from the national park planning period during the 19th century. After the concept of ecological networks was noted in a government report in the United States (President's Commission on Americans Outdoors, 1987), ecological networks were widely applied, and have played a core role in improving city landscapes and achieving a more rational layout and structure of urban green space (Fábos, 2004; Jongman et al., 2004).

Ecological networks are based on the landscape ecology concepts of “irreplaceable patterns” and “best landscape patterns” (Forman and Godron, 1981). Some landscape components are irreplaceable because no other land use or cover type can replace the services they provide; bodies of water and farmland are two examples. “Best” patterns represent landscape patterns that preserve these irreplaceable elements and represent a potentially optimal use of the available space to achieve both ecological and socioeconomic objectives. Ecological networks consist of landscape-level patterns of green space, including farmland, forest, grassland, water areas, and artificial green spaces in urban areas (UPDST, 1998; Franco et al., 2003; Liu et al., 2005). Linehan et al. (1995) described the steps to design one such network: assessment of land cover, wildlife, and habitat, followed by node and connectivity analysis, and finishing with generation and evaluation of the network. They used the resulting network to evaluate forested regions of central New England in the United States.

This method allows researchers to weight the interactions between nodes, while determining the potential paths for flows of materials and energy (Kong and Yin, 2008). In constructing landscape ecological networks, these paths can be determined two ways. First, they can be identified by extracting natural cover and terrain, as in the case of a “blue network” extracted from river corridors (Hoctor et al., 2000) or a “green” network extracted from ecological corridors (Conine et al., 2004). Second, the potential paths between nodes can be determined using a distance-based cost, as described by Zhang and Wang (2006), who determined the minimum distance between two green patches based on minimizing the cost of the flows between them. Socioeconomic activities are regarded as obstacles that disrupt the spread of a network along these paths (Gao et al., 2010), and are difficult to contain within a landscape ecological network. At the same time, all paths represent potential flows (Jim and Chen, 2003), but do not