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Analyzing the spatial pattern of carbon metabolism and its response to change of urban form

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ABSTRACT

Analyzing the correlation between carbon metabolism and urban form could provide new insight for low-carbon city design. The paper analyzed the spatial changes of urban carbon metabolism and also of the urban form from 1990 to 2010, using a combination of GIS method and landscape indices. The study showed that urban center in 2010 increase to 2.2 times that in 1990, which caused the expansion and extension of high carbon emission area in the southeast plain. The evolution of suburbs and outer suburbs was influenced by urban center and fell behind urban center, which caused the opposite change of the medium and low carbon emission area in the periphery of southeast center. The spatial distribution of carbon sequestration was affected by the policies during urbanization, which caused the shrink and fragmentation before 2000 and the recovery of the high carbon sequestration area after 2000. The study could be quite useful for regional land use planning for providing quantitative evaluation.

1. Introduction

Urbanization changed the urban form and also caused the transformation from rural to urban land (Poumanyvong and Kaneko, 2010); thus forming a complex spatial structure (López et al., 2001). Changes in the urban environment resulted in the fragment of the natural vegetation (Tang and Wang, 2007), which greatly imbalanced the carbon emission and sequestration, leading to the differences in carbon metabolism among various regions (Ramamurthy and Pardyjak, 2011). Urban form is usually described as the city layout and the urban morphology. The layout refers to the allocation and arrangement of different land use types, while the morphology covers the change in shape and fractal dimension of a certain type of land use. Till 2006, the CO_2 emission from the urban area made by nearly half of the world population has taken almost 70% of the total amount (IPCC, 2006; http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.html). With urban area being the key area of cutting emission, many countries have started to reweave their planning over the urban form, trying to find ways of low-carbon development through the adjustment of urban morphology and layout, as well as the developing mode (Tian et al., 2014). Beijing is a good example to explore the spatial variations of urban carbon metabolism and discover its response to the changes in urban form. The fast urbanization in Beijing for the last several decades has taken up a large amount of land and used up a great deal of energy, which deteriorated the carbon balance within the city. At the same time the irregular expansion and low-density development led to the intense spatial heterogeneity of the carbon metabolism. The results could provide theoretical basis to the urban planning.

Different urban form could cause various society and environmental consequences (Holden, 2004). Scholars started to focus on the connection between environmental behavior and urban form (Alberti, 1999), topics covered the energy efficiency in the urban area (Chen et al., 2011), urban heat distribution (Pauleit et al., 2005), energy consumption of traffic (Tang and Wang, 2007) and other aspects. In these studies, urban form could be measured through various indexes, like the population density, the grain (the diversity of the land use) and connectivity (the inner connectivity and the cycling relationship between human activities and goods) used in Alberty's study that comprehensively evaluated the interactions between the urban form and the environment behavior of the carbon source and carbon sink (Alberti, 1999). While in the study of Liu et al., they used indexes like form, compactness ratio, elongation ratio and population density to discuss the connection between the

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ecological efficiency of the city and its form (Liu et al., 2012). However, the current studies mainly focused on the evolution of the inner structure of the city, in lack of the insight from the perspective of urban metabolism and the clear expression of the correlation between carbon metabolism and the urban form in spatial, which is the direct observation of the extension of urbanization.

The urban initially referred to the spatial allocation of land use types (Anderson et al., 1996; Chen et al., 2011). It is because one third of the carbon emission in the urban area is due to the change in land use and cover change (IPCC, 2006; http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.html) that made it reasonable to attach great importance to the study of the urban carbon balance from the viewpoint of change in land use (Houghton and Goodale, 2004; Kauppi et al., 1992). Pauleit and Duhme (2000) dug into the interaction between carbon emission process and the land use. While based on the carbon accounting, Christen et al. (2011) took the change in carbon storage due to the land use and cover change into consideration. The changes in the urban form also conclude the change in morphology (Alberti, 1999). Urban morphology could be resulted from the staggered distribution and changes of various land use types. The urban morphology study origins from the fractal study in geometry. In 1960s, University of Michigan started the fractal studies and discovered the irregular of urban morphology which could be described by fractal dimension. Then Batty and Longley (1987) first carried on the urban morphology study using fractal dimension. They used the ratio between area and perimeter to analyze the fractal dimension of the different land use type. Afterwards, the indicators of fractal dimension developed the quantification expression of the relationship between area and radius (White and Engelen, 1993). Other research further performed the fractal analysis with box accounting dimension (Czamanski et al., 2000).

As the development of landscape ecology, the mature accounting method and software has been built to quantitatively evaluate the urban form, which could be applied into the research on urban form changes during urbanization (Luck and Wu, 2002; Wu et al., 2016) and the long term study (Chen et al., 2011; Poelmans and Rompaey, 2009). As the accounting method of urban form developing, researchers begin to pay attention to the relationship between urban form and its environmental behavior. Different indicators were used to perform such studies, for example water resource, heat distribution, carbon storage and so on (Pauleit et al., 2005; Poumanyvong and Kaneko, 2010). Meanwhile, study already demonstrated the influence of urban form on carbon budget (Whitford et al., 2001). Such study could be further used to diagnose the urban diseases from fast development (Chen and Wang, 2013), such as the negative correlation between urban form and eco-efficient. Besides the emission of SO_2 and disposal of waste studied in the research, the author also pointed out CO_2 emission as an important indicator of the urban environmental behavior (Liu et al., 2012).

Urban metabolism could provide additional information for relationship study between urban form and its environmental behavior. Urban metabolism could quantitatively evaluate the input, output and storage of energy, water, waste and so on. The information makes it importance to study urban form with urban metabolism (González et al., 2013). In the study of Zhang et al., the potential correlation between urban morphology and carbon metabolism was performed (Zhang et al., 2014). The landscape indices were applied to describe the changes in shape and fractal dimension of Beijing city from 1990 to 2008. Meanwhile, the fragmentation and aggregation of patches of carbon metabolism was analyzed in the paper. However, the study only focused on the core-built up area and lack of the correlation analysis through the whole city. Nevertheless, these studies provide a basis for future study of response relationship between urban morphology and carbon metabolism in spatial.

Overall, Using Beijing city as an example, the following questions was discussed in this study: the changes in spatial pattern of carbon metabolism and the changes in the fractal dimension in the urban area. Finally the correlation between them was carried on in the paper. To do so, we organized the structure of paper as follows: The first, the spatial pattern of carbon metabolism was analyzed using GIS software and landscape indices and the variations of different grade carbon patches were analyzed. Next, the spatial distribution through the whole city was considered and the fractal dimension and area of urban land of different counties was calculated. Finally, we explored the response relationship between urban morphology and carbon metabolism in spatial.

2. Methodologies

2.1. The spatial pattern of carbon metabolism

The urban carbon metabolic processes mainly refer to the carbon flows between the biosphere and the atmosphere, as well as the potential carbon transition processes that can lead to changes of carbon source and sink. Meanwhile, the city can be abstracted as a system consisting of different components. Each of the components varied in their spatial pattern and morphology. They are closely linked with each other in urban carbon metabolism, and have frequent carbon transitions which lead to changes in the stock and flux of different land components. The spatial differentiation, which occurs in the processes of carbon emission, carbon sequestration and the mutual carbon transition sub-processes, forms the unique spatial pattern of urban carbon metabolic processes.

In our past studies, we have calculated the carbon metabolic rate based on different land components. According to the accounting methods and results of Zhang et al. (2014), we obtained the carbon emission and sequestration of five periods (1990, 1995, 2000, 2005 and 2010) with the unit of kg/yr. After imported the carbon fluxes results into Arcmap 10.0, we got the spatial distribution pattern of the carbon sources and sinks. We then applied the Natural Breaks method, and did some adjustments based on the automatically optimized spatial-division results (using the Jenks Optimization method) to make sure that the grading standards of the five stages were the same. (Table 1)

Based on the spatial-division result, we extracted the carbon metabolic patches of different grades, including 6 grades of carbon emission patches and 6 grades of carbon sequestration patches, and quantitatively analyzed the spatial morphological changes of different carbon metabolic patches using the landscape indices method. We chose the following indicators to evaluate the fragmentation and aggregation of carbon patches: the aggregation index (AI), the Euclidean nearest-neighbor index (ENN), and the change in the number of patches (NP). AI was selected to indicate changes of the urban agglomeration degree. AI ranges from 1 to 100, and it increases when aggregation increases. The formulations for the variations of landscape indices are shown in Table 2. The value of ENN is larger than 1, and a larger ENN indicates a greater distance between the patches, as well as a greater degree of separation. The value of NP is later than 0, and it increases with the increase of patch number, which reveals a greater degree of fragmentation.

According to the spatial variations of the carbon metabolism, we identified the dynamic changes of carbon metabolic patches in different grades. Applying the landscape indices method, we quantitatively identified the aggregation and fragmentation of carbon metabolism patches. On the basis of these qualitative interpretation and quantitative measurement, we summarized the distribution and variation characteristics of carbon metabolism spatial patterns,