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A spatio-temporal analysis of low carbon development in China's 30 provinces: A perspective on the maximum flux principle

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ABSTRACT

This study constructed a multidimensional indicator system to evaluate low carbon development of the whole country and 30 provinces in China from 2003 to 2013, based on the maximum flux principle, which reflects the dynamic evolutionary process of low carbon development. Then k-means cluster analysis was used to classify 30 provinces into three grades (highest, medium and lowest) according to their average low carbon development level. Finally, Moran's I was used to investigate the spatial correlation of low carbon development in China. The simulation results show that the national low carbon development level increased with fluctuations from 2008 as the nation paid high attention to low carbon development, and the provincial low carbon development is unbalanced, which is closely related to the socioeconomic conditions, resources endowment and geographical locations. For each province, the development level of different evaluative dimension grows unequally. For each grade, the provinces of highest grade have good performance in energy and environmental dimensions and the provinces of medium grade have good performance in society or the economic dimension, but the provinces of lowest grade have a lower development level in all dimensions. There is significant positive spatial dependence and cluster characteristics in low carbon development in China. In general, high-level provinces are distributed in southern China while low-level provinces are mainly located in northern China. The high-level provinces should perform their demonstrating functions and promote low carbon development in their surrounding areas.

1. Introduction

Nowadays, global climate change has become the focus of the international community. Climate change, a global issue concerning the interests of the whole world, causes serious environmental problems such as fire, sea level rise (Kuhfuss et al., 2016), severe drought and flooding, as well as other natural disasters that threaten human survival (Pumo et al., 2016). The United Nations Climate Change Conference (COP 21) was held in Paris in December 2015 and set a goal of limiting global warming to less than 2 °C above the pre-industrial levels. In this context, a low carbon development pattern is considered to be the best choice for the world in the long term. The concept of low carbon development puts forward a new sustainable development pattern with low energy consumption, low pollution and high energy efficiency to reduce carbon emission and cope with global climate challenges (Su et al., 2012). As the basic unit of administrative management and the centre of human production and living, cities play an important role in low carbon development as they are the largest contributor of carbon emission (Su et al., 2013). The acceleration of urbanisation, increase in energy demand and resource intensity cause environmental problems which are in conflict with the harmonious development between humans and nature (Van Staden et al., 2014). Finding a right solution to make cities healthy with sustainable development is necessary. In recent years, policy makers and scholars have paid more attention to cities' sustainable development. The concept of a low carbon city has been mentioned widely and is a hot topic in city development. Scholars mainly discuss how to promote the development of low carbon cities, and evaluate the low carbon development of a city in the existing literature (Baeumler et al., 2012; Dou et al., 2016).

With regard to low carbon city construction, some scholars select one single sector or a small part of a city to study the essential elements that contribute to low carbon city development. Cities have pressures to

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provide jobs, housing and public services. Tackling these issues requires extensive efforts to solve the problems of energy efficiency, traffic congestion, waste and pollution (Baeumler et al., 2012). The transportation sector, one of the sectors with significant energy consumption, has contributed to larger carbon emission. Policies of energy saving and carbon emission reduction such as natural gas vehicles and being transit-oriented across the transportation sector are effective strategies in moving towards low carbon city development (Phdungsilp, 2010; Peng et al., 2015; Dou et al., 2016; Dalianis et al., 2016; Du et al., 2017; Liu et al., 2017). In the building sector, international cooperation, macro-level management, development of low carbon theories and technologies and other issues are important factors which promote the development of low carbon buildings. Furthermore, building energy consumption structure plays an important role in low carbon city development (Huang and Mauerhofer, 2016; Shi et al., 2015). In the industrial sector, industrial symbiosis provides a system of innovation to utilise the industry to fight against climate change and pursue low carbon city development (Dong et al., 2013, 2014). City development faces rising waste generation, and landfill gas utilisation is identified as a measure which can achieve the highest carbon emission reductions (Papargyropoulou et al., 2015). To achieve low carbon city development, energy efficiency development strategies are expanding into other priority resources (e.g. water) through an important integrated approach (Du et al., 2016; Topi et al., 2016). Other aspects such as human cognition, stakeholders' perceptions and values impact cities to move towards low carbon development (Olazabal and Pascual, 2014).

To evaluate the effectiveness of various low carbon city development strategies, usage of appropriate evaluation models, which include indicator systems and methods, are essential. The multiple indicator systems in the existing literature cover economic development, social progress, energy structure and environmental quality, for which various evaluation methods have been used. For instance, Price et al. (2013) evaluated low carbon development at the provincial level using an indicator system covering the energy end-use sector (industry, residential, commercial, transport, electric power). Zhou et al. (2015a,b) used the driving force-pressure-state-impact-response (DPSIR) framework to evaluate the responses in existing global low carbon city initiatives. Zhou et al. (2015a,b) developed the eco and low carbon indicators tool for evaluating cities (ELITE cities) to measure low carbon city progress through 33 key indicators which include energy, water, air, waste, mobility, economy, land use and social health. Lin et al. (2014) evaluated low carbon development in Xiamen using a novel evaluation system, which integrated city-level carbon intensity targets with low carbon city indicators through a decomposed method, and considered carbon emissions from energy use, industrial processes, agriculture, forestry and waste. The above evaluation models evaluated current low carbon performance and inform policy makers of appropriate low carbon city strategies so as to promote cities' healthy development.

Since its economic reform and liberalisation of its markets over 30 years ago, China has achieved great accomplishments in economic and social development. Nevertheless, rapid economic growth has been associated with worsening environmental pollution and ecological destruction. Against this background, low carbon development is the only viable path which will solve environmental problems and achieve sustainable development in China. The idea of "low carbon" has become one of the major concerns in China's urbanisation and low carbon city policy is an important development strategy at national and local levels (Liu and Qin, 2016). To actively promote and guide the development of low carbon city, the Chinese government initiated a low carbon pilot test for provinces and cities in 2010. The first-batch pilot projects included five provinces and eight cities (Khanna et al., 2014). In 2012, to search for methods to control greenhouse gas emission in different areas, the second batch of pilot projects included 29 cities. As of now, China has confirmed six low carbon pilot provinces (Guangdong, Liaoning, Hubei, Shaanxi, Yunnan and Hainan) and 36 low carbon pilot cities (Fig. 1). The low carbon pilot projects are being carried out across the whole country. The pilot projects provide practical experience and identifies appropriate strategies for localised low carbon development which can be applied to cities all over the country (Wang et al., 2015). An increasing number of scholars are focusing on low carbon development in China through case studies, such as in Wuxi (Dienst et al., 2013), Suzhou (Liu et al., 2012a,b), Chongqing (Liu et al., 2012a,b), Beijing (Zhang et al., 2011) and Shanghai (Lehmann, 2012; Chen and Zhu, 2013).

To evaluate low carbon development in China, we used a novel theoretical framework and evaluation method called maximum flux principle (MFP), which reflects the dynamic mechanics of low carbon development. In this theoretical framework, a low carbon city is viewed as an open dynamic complex system and various driving forces from the competitive environment support its development. We introduce the concept of maximum flux to describe the interactions between different driving forces, and applied MFP to establish a new model to evaluate low carbon development in China. The previous evaluation methods regarding low carbon development overlook the complexity and dynamics of the low carbon development process, that is, they have not considered the interaction among different driving forces. The maximum flux principle fills that gap and becomes an effective method to solve the problems in complex systems, which reveals the dynamic development process of complex systems.

2. Research methods

In this section, we introduce the maximum flux principle (MFP) and global spatial auto-correlation model. The MFP is used to calculate low carbon development levels and Moran's I, the core statistic of global spatial auto-correlation model, is introduced to investigate spatial correlation in low carbon development.

2.1. The maximum flux principle

As an open dynamic complex system, a low carbon city continually changes resources, information, capital and energy with other cities and it evolves continually under nonlinear dynamic interactions of the above driving forces. That evolutionary process produces additional flux to support low carbon development of the city. Each driving force is an agent and all agents are numbered$x_1,x_2,...,x_n$, which are expressed by a vector $x = (x_1,x_2,...,x_n)$. Similar to classical statistical theory, all possible micro-states constitute a continuous scope in the Γ space and $dx = dx_1 dx_2 \cdots dx_n$ is defined as a volumetric unit in the Γ space. When the system exists within the volumetric unit dx at time t, its probability for this state is $\rho(x,t)dx$, where $\rho(x,t)$ is the density function of the ensemble and satisfies the normalisation condition $\int \rho(x,t)dx = 1$. We define J as the flux within the system in the volumetric unit dx at time t. The function J which describes the interactions among agents can be written as (Chai and Shoji, 2002; Wang et al., 2010):

$$J = \eta + \sum_i \gamma_i x_i + \sum_{ij} \gamma_{ij} x_i x_j + \sum_{ijk} \gamma_{ijk} x_i x_j x_k + \sum_{ijkl} \gamma_{ijkl} x_i x_j x_k x_l + \cdots \tag{1}$$

At the same time, we define the averaged flux function over all possible micro-states as follows:

$$\bar{J} = \int \rho(x,t) J(\rho) dx \tag{2}$$

The constraints of a low carbon city system generally include a variety of macroscopic conservation equations and temporal-spatial boundary conditions, such as conservation of energy resources and capital. These constraints can be transformed into a conservation relationship among all the agents and expressed by one-to four-order interaction momentum quadrature as follows: