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Assessing sustainability of urbanization by a coordinated development index for an *Urbanization-Resources-Environment* complex system: A case study of Jing-Jin-Ji region, China

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ABSTRACT

China's rapid urbanization has produced a number of resources and environmental problems, making it necessary to provide a scientific basis for the promotion of sustainable urbanization. This study integrates systems theory with complexity science to create an Urbanization-Resources-Environment complex system (URE) to assess the sustainability of urbanization, beginning by conjoining a theory of urbanization and ecological environment coupling. We developed a comprehensive coordinated development index for URE (URECDI) to represent the internal connectivity and influence between the urbanization, resources and environmental subsystems, and also indicate the sustainability of urbanization. This study analyzed trends observed in URE for 13 cities in the Jing-Jin-Ji region (JJJ) of China, using statistical data collected from 2005 to 2015. The main results are: (1) urbanization efficiency, resource utilization efficiency and environmental quality are the largest influences on the indices, which indicates that they are key factors in the behavior of URE; (2) coordination between subsystems of URE within JJJ was not good, but showed an increasing trend during 2005–2015; and (3) URECDI indicated significant differences between 13 cities, which suggests that we can increase coordination within URE by implementing a zoning strategy, and adjusting policies and investment to favor low-coordinated cities. The coordinated development index can reveal the overall characteristics of URE and ensure regionally sustainable urbanization.

1. Introduction

In recent times, urbanization has developed globally at an unprecedented rate. In the last 50 years, the global urban population has grown by nearly 20%. By 2008 over 50% of the global population lived in urban areas; in 2016, the extent of global urbanization reached 54.3% (World Bank Group, 2017). Urbanization is one of the most significant human activities to affect Earth. It is a process that concentrates populations in towns, cities, and metropolitan areas and alters land use with the urban landscape (Angel, 2012). Urbanization includes a complex geographical relationship between humans and the land surface as well as associated economic and social activities (Pitman, 2005; Friedmann, 2006; Fragkias et al., 2017). Urbanization drives global economic growth, affects global and regional resources, and changes the natural environment on many scales. It fundamentally changes the ecology of a region (Tratalos et al., 2007; Grimm et al., 2008; Liu et al., 2011). Urban expansion alters land use and land cover, affects ecosystem biodiversity, modifies watershed hydrology, and changes biogeochemical cycles through waste discharge (Pataki et al., 2011; Kong et al., 2012; Lin et al., 2015; Schneider et al., 2015; Kalantari et al., 2017).

After reform and opening-up in China, there have been benefits from rapid economic development, and urbanization has increased significantly (Bai et al., 2014; Yin et al., 2014). From 1978 to 2015, the proportion of China's population that lived in cities increased from 17.9% to 56.1%, with an average annual growth rate of 1.03%, which is much higher than in the rest of the world over the same period (National Bureau of Statistics, 2006–2016a). However, China's rapid urbanization has also caused a series of resource-related and environmental problems, including loss of arable land, water and energy shortages, habitat fragmentation, increased carbon emissions, and particulate matter pollution (Wang et al., 2013; Li, 2015; Xu et al.,

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2015; Li et al., 2016; Liu et al., 2016; Wang and Liu, 2017). Air and water pollution are intense, and other environmental contaminants abound in China's major cities and urban areas (Fang et al., 2010; Wang et al., 2017). For example, monitoring data indicate the severity of $PM_{2.5}$ pollution in China's urban agglomerations (Fang et al., 2016c). Many scholars are interested in the relationship between urbanization and the natural environment because of the effects of rapid urbanization in China. The natural environment and the built urban environment form a complex system with multiple feedback loops. They are coupled in a nonlinear relationship which can be represented by an inverted U-shaped or an S-shaped curve (Wang et al., 2014; Fang et al., 2016b; Zhao et al., 2016; He et al., 2017).

Within systems theory and complexity science, a system is defined as complex when its constituent elements cannot explain the overall characteristics of the system due to their nonlinear links (Gallagher and Appenzeller, 1999; Bailey, 2001; Espinosa and Walker, 2011). A complex system has many characteristics, including numerous components, rich and complex interactions between them, openness, and being dynamic rather than in equilibrium (Cilliers and Spurrett, 1999). There is an urban–environment nexus that includes the use of both natural and built resources and which can be thought of as an Urbanization-Resources-Environment (URE) complex system which is an open, complex, and dynamic system, and which has a formal structure and a certain functionality (Xie et al., 2016). Within URE, urbanization (U), resource (R) and environmental (E) subsystems are individually complex systems that interact nonlinearly, and the nature and activity of their interconnections determine the development of the URE complex system. If one or more of the interconnected subsystems act abnormally, then the overall coherence and operation of URE will also be abnormal (Kelly et al., 2007).

The urbanization and environmental coupling (UEC) model treats urbanization, resources, and the environment as independent systems with complex interactive forcing relationships. However, from a complex systems perspective, the three systems are inseparable and thus form a larger system, URE, the coherence and internal state of which indicates the sustainability of urbanization (Holland, 1996; Fang and Wang, 2013). URE, in contrast to UEC, emphasizes the integrity, structure, and overall evolution of the subsystem couplings. URE is an integrated dynamic system with a complex structure which is always evolving from low-level disorder to high-level order (Li et al., 2010). Sustainable development theory holds that the state of coordination between subsystems can provide a criterion for judging whether the system tends towards high-level order, which is an indicator of sustainable development (Lélé, 1991; Jordan et al., 2010; Wang and Zhou, 2016).

Rapid urbanization in China has forcibly affected the environment, while environmental change has, in turn, affected sustainable urbanization, especially in major cities and urban agglomerations which determine economic development and future urbanization (Fang et al., 2016a). It is necessary to analyze and understand the interactions between the urbanization, resources, and environmental subsystems of URE to realize sustainable urbanization. Suitable management measures should be implemented without delay.

This paper attempts to deepen the understanding of the overall process of connectedness between urbanization, resources and environment and to find the direction of sustainable urbanization by outlining a complex system theory of Urbanization-Resources-Environment (URE). This research has two goals: to develop an index that accurately represents the overall effect of the three subsystems on the sustainability of urbanization; and to present a case study of 13 cities in Jing-Jin-Ji region to demonstrate the use and effectiveness of the index. First, starting with the established urbanization and environmental coupling (UEC) theory, we develop a coordinated development index for URE (URECDI) to analyze the degree of interaction between U, R, and E subsystems and provide an indicator of the sustainability of urbanization. Second, we use URECDI to analyze the sustainability of urbanization for 13 cities in Jing-Jin-Ji region (JJJ) during 2005–2015.

Fig. 1. Location and extent of JJJ.

The remainder of this paper is organized as follows. Section 2 describes the study area, data screening, and the methodology used to establish a value for URECDI. Section 3 discusses the models developed in Section 2, analyzes the results obtained for 13 cities in JJJ, and assesses the efficacy of URECDI. Section 4 sets out the main conclusions derived from the study.

2. Materials and methods

2.1. Study area

Jing-Jin-Ji region (JJJ) includes Beijing, Tianjin, and Hebei, which includes Shijiazhuang, Tangshan, Qinhuangdao, Handan, Xingtai, Baoding, Zhangjiakou, Chengde, Cangzhou, Langfang, and Hengshui (Fig. 1), all having different development characteristics. JJJ is one of the three largest urban agglomerations in China (the others are Yangtze River Delta and Pearl River Delta). It covers 217,156 km^2, 1.9% of China's territory, and in 2015 it had a population of 111.42 million and GDP of 1,129 billion dollars. JJJ is rapidly urbanizing; the urban population of the region increased from 30.3% in 1990 to 62.7% in 2015, an average annual growth rate of 1.3%. Table 1 shows the economic indicators and urbanization rates for JJJ in 2015. The rapid development underlying Table 1 is likely to put pressure on both resources and the environment.

JJJ has become an area of serious water shortage, air pollution, water pollution, and conflict between economic development and environmental sustainability because of rapid urbanization and economic development (National Development and Reform Commission, 2015). Sustainable urbanization in JJJ faces enormous challenges.

2.2. Data pre-processing

The data used in this paper were mainly obtained from China Statistical Yearbook (2006–2016) (National Bureau of Statistics, 2006–2016b), China Statistical Yearbook on Environment (2006–2016) (National Bureau of Statistics and Ministry of Environmental Preservation, 2006–2016), China City Statistical Yearbook (2006–2016) (National Bureau of Statistics, 2006–2016a), China Urban