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Spatiotemporal interaction between ecosystem services and urbanization: Case study of Nanjing City, China

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ABSTRACT

Ecosystem services (ES) are benefits derived from ecosystems and have great significance in sustainable development. Rapid transformations of materials, energy and information flow in ecosystems are impacted by urbanization. Some pressures damage the balance of the ecosystem, such as transformations of land use and changes to industrial structure. Therefore, a clear understanding of the relationship between ES and urbanization provides new insight into urban sustainable development planning and decision-making. Although plentiful literature has focused on the topic, few studies assess the spatiotemporal interactions between ES and urbanization. Nanjing lies in the Yangtze River Delta Economic Zone, China and has been experiencing rapid urbanization. We use decoupling and spatial correlation analysis to discuss the spatiotemporal interaction among four ecosystem services and urbanization in Nanjing. The results show that there is mostly weak decoupling between ecosystem services and urbanization; the index of urbanization and ecosystem services exhibits spatial autocorrelation not only by themselves but also with each other; urbanization damages ecosystem services, especially in the food supply, which declined by 17%. These results indicate that we can predict changes to ecosystem services through urbanization, optimize space provisioning and human activities, enrich studies on ecosystem services and guide sustainable urban development.

1. Introduction

Urbanization, one of the most common societal and economic phenomena in the world, is a process of economic development, population increase, expansion of urban land use and lifestyle change. Economic development is the basis, population increase and regional expansion are representational performance metrics, and living standard improvement is the final goal (Huang and Fang, 2003). According to relevant studies, urban populations constituted more than 54% of the total population at the end of 2014 and are projected to reach 66.4% of the human population by 2050. Chinese urban populations will account for 75.8% of the global population (United Nations, 2014). At the same time, urban areas are expanding faster than urban populations (Elmqvist et al., 2013). Urbanization drives global environmental change and economic transition directly with the rapid development of economy, population growth and increasing area of urban construction land (Grimm et al., 2008). Urbanization is a double-edged sword. On the one hand, rapid urbanization improves the effects of urban resources and energy and provides better services including education, culture and social security. On the other hand, it also generates a series of social, economic and environmental problems, such as traffic congestion, the heat island effect and biodiversity loss (Bloom et al., 2008; Wu, 2008). Rapid urbanization seriously aggravates pressure on the sustainable development of human beings and ecosystems.

Ecosystem services (ES) are the environmental conditions and utilities for the survival and development of human beings. One definition of ES is “goods and services humans obtain from ecosystems directly or indirectly” (Costanza et al., 1997). ES are divided into four main categories by Millennium Ecosystem Assessment (Millennium Ecosystem Assessment, 2005): provisioning services (e.g., food production, water, fiber and fuel supply), regulating services (e.g., carbon storage, air purification), support services (e.g., biodiversity), and cultural services (e.g., recreation opportunity and historical recognition). There are many international orientations, such as the classification of ecosystem services (Wallace, 2007; Li et al., 2013), the interrelation of ecosystem services (Costanza, 2008), the forms and influencing mechanisms of ecosystem services, and the spatial mapping of ecosystem service assessments. In China, the study includes the meaning, classification and assessment of ecosystem services (Zhang et al., 2011), especially focused on assessing the value of different types of ecosystem services on

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national and regional scales. With the completion of the Millennium Ecosystem Assessment (Leemans et al., 2003), research on ecosystem services has gradually extended beyond the stage of pure static value evaluation, focusing on the mapping of ecosystem services (Yoshimura and Hiura, 2017) and the influence of ecosystem services on human welfare, with more attention paid to the regional differences of ecosystem services and the correlation of spanning spatial scales. Due to the regional differentiation of physical geographical factors, ecosystem services have remarkable spatial heterogeneity and regional differences (Swallow et al., 2009). Because humans are increasingly modifying natural ecosystems, social economic and cultural factors, which are closely related to the activities of human beings, play a role in the spatial differentiation of ecosystem services. The spatial inequality of ecosystem services is further aggravated by the frequency and intensity of resource use in different regions. Ecosystem services, as the bridge that links ecosystems and social systems (Su and Fu, 2013), have become a research hotspot in ecology, geography and environmental sciences (Buyantuyev and Wu, 2009) and now are facing increasing pressures from intensifying urbanization (Estoque and Murayama, 2013; Su et al., 2012).

Recognizing urban development as one of the main drivers of ES change, the effects of urbanization on ES have been widely discussed (Baró et al., 2017; Holt et al., 2015; Qiu et al., 2015; Wan et al., 2015), and they interrelate and interact with each other. First, urbanization is the main driving force for the change in ecosystem services and processes (Ran et al., 2006; Amundson et al., 2015). Many studies show that urbanization places intense pressure on ecosystem situations. The change in land use reduces soil productivity and regulatory ability (Lavellea et al., 2006). Population consolidation and the input of pollutants from industry and agriculture exceed the self-purification capacity of ecosystems, and pollutant buildups endanger the functions of ecosystem services (Sutton et al., 2016). The increasing rate of urban construction land observably damages the exchange of material and energy within an ecosystem and causes ecosystem services to quickly decline. Some scholars have used models to simulate the processes of urbanization and ecosystem services and believe there is an inflection point for the impact of urbanization on ecosystem services (Antrop, 2000; Pannell, 2002; Mulligan, 2013). When urbanization reaches a certain level, and economic development and technology are upgraded, the ecological regime will take a favorable turn, and the stage of coordinated development of urbanization and ecosystem services will begin (Bateman et al., 2013). Second, ecosystem services are counterproductive to the process of urbanization. Urbanization is restricted and constrained by the ecological environment, and after the degradation of ecosystem services reaches a certain threshold (Peng et al., 2017), the social and economic development of a city will be restricted. In general, ecosystem services degradation will directly endanger the wellbeing of contemporary human society and reduce the benefits future generations derive from the ecosystem.

To maintain sound development of urbanization and maximize the benefits of ecosystem services, it is necessary to understand, optimize and promote coordinated and orderly development between ecosystem services and urbanization (Grêt-Regamey et al., 2016), with an emphasis on the dynamic evolution of ecosystem services and time-coupling characteristics. At present, there are a few quantitative studies on the correlation analysis of changes in urbanization and ecosystem services. Although various studies have found a causal relationship between urbanization and ecosystem service degradation, few studies assess the spatiotemporal interactions between ES and urbanization. At the end of June 2018, there were 24,003 references to “Ecosystem services”; 55,375 with “Urbanization” and 69,788 with “spatiotemporal” in the subject were retrieved from the Web of Knowledge database, respectively. When the search terms are changed to “urbanization” and “ecosystem services,” “spatiotemporal” and “urbanization,” and “spatiotemporal” and “ecosystem services,” 1111,792 and 240 references are retrieved, respectively. However, only 38 articles were retrieved when the search terms were “spatiotemporal” and “urbanization” and “ecosystem services.” It can be seen that less attention has been paid to exploring the spatiotemporal interaction between ecosystem services and urbanization.

Nanjing, one of China’s most famous ancient capitals, has experienced rapid urbanization since the 2000s (Xu et al., 2007), which has caused many changes in natural landscape and environmental deterioration. It is urgent to analyze the spatiotemporal heterogeneity and dependence of urbanization and ecosystem services along with the rapid urbanization of Nanjing. Here, we aimed to i) clarify the changing process of urbanization and ecosystem services spatially; ii) apply spatial correlation and decoupling to analyze the spatiotemporal correlation between urbanization and ecosystem services; and iii) provide suggestions and guidance for the coordinated development of urbanization and ecosystem services in the future.

2. Materials and methods

2.1. Research area

Nanjing is in the Yangtze River Delta, Jiangsu Province, Eastern China (Fig. 1) and is traversed by the Yangtze River. The terrain is dominated by hilly land in the area, followed by plains, rivers and lakes throughout. It lies in the northern subtropics; the climate is mild and rainy, with four distinct seasons and a hot, rainy season; an annual average temperature of 15.4 °C; and an annual average precipitation of 1106 mm (NBS, 2001; Li et al., 2016). Between 2000 and 2015, the cultivated land area was reduced to $7.0 \times 10^4\,hm^2$, which accounts for 10.5% of the total area of Nanjing; because of the rapid urbanization, construction land use has reached $8.40 \times 10^3\,hm^2$ of ecological land.

2.2. Methods

2.2.1. Ecosystem services selection and evaluation

The study of ecosystem services has developed on different scales due to different classification frameworks. The selection of ecosystem services will show different importance due to the change of scale (Haase et al., 2012). At a global or national level, every natural capital and ecosystem service must be considered as comprehensively as possible. On a smaller urban scale, however, it makes more sense for policymakers to study the ecosystem services that have the greatest impact on local residents. Considering both the scientific and practical situations in Nanjing, we selected food supply, carbon sequestration, soil water storage, air pollution removal, habitat suitability and recreation potential as indicators to reflect the four ecosystem services. For the specific formula, see Table 1 and the Supplementary Material.

2.2.1.1. Food supply. Crop yield reflects the food supply of arable land and is significantly and positively correlated with the cultivated land quality. The annual grain yield was used to assess the food supply capacity of the ecosystem. The cultivated land quality data were derived from the Jiangsu farmland classification database for 2000 and 2015 through a formula (Table 1) establishing the relationship between grain yield and quality of cultivated land.

2.2.1.2. Carbon sequestration. Net primary productivity (NPP) is the energy fixed per unit area per unit time left by a green plant after breathing or the organic matter produced, and it can represent the carbon fixation capacity of cities. The Carnegie-Ames-Stanford approach (CASA) calculates the total amount of NPP (see SM1.1); CASA consists of remote sensing data, temperature, rainfall, solar radiation, vegetation type, and soil type and is driven by a solar energy utilization model.

2.2.1.3. Soil water storage. We use surface runoff to characterize the ecosystem soil water storage. The calculation is based on the Soil