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On the spatial relationship between ecosystem services and urbanization: A case study in Wuhan, China

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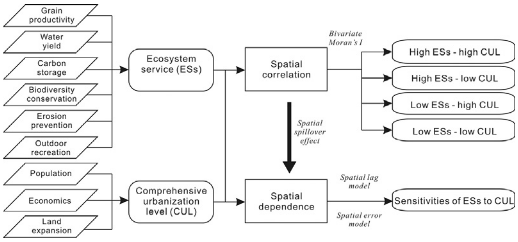
HIGHLIGHTS

- Various models and multisource data were integrated to estimate ecosystem services (ESs) as well as urbanization.
- The bivariate Moran's I methods were employed to test and visualize spatial correlations between ESs and urbanization.
- Spatial regression models were used to describe the spatial dependence of ESs on urbanization.
- Spatial spillover effect existed in the relationship between ESs and urbanization.
- ESs of different type showed varied spatial dependence on urbanization.

GRAPHICAL ABSTRACT



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ABSTRACT

A clear understanding of the relationship between ecosystem services (ESs) and urbanization provides new insight into urban landscape planning and decision making. Although a considerable amount of literature has focused on this topic, few studies address the spatial interactions between ESs and urbanization, especially at the local scale. Various models and multisource data were integrated to estimate ESs and urbanization in Wuhan City, China. The bivariate Moran's I methods were employed to test and visualize the spatial correlations between ESs and urbanization. Spatial regression models were used to describe the spatial dependence of ESs on urbanization. Our results showed that all ESs have globally negative spatial correlations with urbanization, but focusing on local scale allowed spatial correlations to be categorized into four types: high ESs and high urbanization, high ESs and low urbanization, low ESs and high urbanization, and low ESs and low urbanization. Spatial regression models were identified as more suitable to measure the spatial dependence of ESs on urbanization, as they account for the effects of spatial autocorrelation. Among ESs, biodiversity conservation was the one most sensitive to increased urbanization, followed by outdoor recreation, water yield, grain productivity, carbon storage, and erosion prevention. The spatial exploration of the relationship between ESs and urbanization provides practical guidance for urban development planning and environmental protection.

1. Introduction

Urbanization, along with population aggregation and economic development, has been recognized as a main force driving environmental

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and ecological change (Li et al., 2012; Seto et al., 2012). Urban development causes natural ecosystems to transform into human-dominated or human-nature-coupled ecosystems (Huang and London, 2012; Qiu et al., 2015). Within the ecosystems, structure (e.g., vegetation coverage and soil quality) and processes (e.g., animal mitigation) are dramatically changed (Eigenbrod et al., 2011; Grimm et al., 2008; Long et al., 2014). Ecosystems are facing increasing pressures from intensifying urbanization (Estoque and Murayama, 2013; Su et al., 2012). How to assess the ecological effects of urbanization and alleviate adverse effects has become a concern for urban landscape planners and decisionmakers worldwide.

The concept of ecosystem services (ESs), which refers to “goods and services humans obtain from ecosystems directly or indirectly,” provides a tool to bridge ecosystem and human welfare (Costanza et al., 1999). According to the Millennium Ecosystem Assessment (2005), there are four main categories of ESs: provisioning services (e.g., food production, water supply, and fiber and fuel supply), regulating services (e.g., climate regulation, carbon storage, natural habitat protection, and air purification), supporting services (e.g., biodiversity), and cultural services (e.g., outdoor recreation and historical recognition). All services can be assessed from three perspectives: ES supply (the potential of ecosystems to deliver ESs), ES demand (the amount of ESs required or desired by society) and ES flow (the actual production of ESs used by humans) (Baró et al., 2016; Bastian et al., 2013; Burkhard et al., 2014; Villamagna et al., 2013). Many monetary and non-monetary approaches have been proposed to assess ESs, and these can generally be divided into two categories: primary data based (service values are calculated using models for ecological processes and data for ecological elements) and biome or land use and land cover (LULC) proxy based (each LULC type is assigned a value for corresponding ecosystem service) (Su et al., 2014). Due to their ability to represent ecological elements and functions, as well as the abundant methods for qualification and visualization that they provide, ESs have become prevalent indicators for characterizing ecosystem change in the study of ecosystem-human interactions (Jing and Zhou, 2016; Su et al., 2012; Zhang et al., 2017).

Based on the recognition of urban development as one of the main drivers of ESs change, the effects of urbanization on ESs have been widely discussed in the literature (Baró et al., 2017; Holt et al., 2015; Mach et al., 2015). Wan et al. (2015) found the temporal relationship between total ESs value and urbanization level exhibits an irregular inverse ‘U’ shape in a region; that is, at the early stages of urbanization, the total ESs value increases, but it declines at later stages of urbanization. They accordingly utilized curve regression to assess this relationship. Peng et al. (2017) used linear regression to estimate the linear relationship between total ESs value and three urbanization indicators, and they further identified the response thresholds of total ESs value to the three indicators. Other studies identified spatial heterogeneity in the relationship between ESs and urbanization and explored the nonstationary dependence of ESs on urbanization from a geographic perspective. Li et al. (2016) found that changes of ESs (food supply, carbon sequestration, soil water storage, air pollution removal, habitat suitability, and recreation potential) vary in different types of area (i.e., developing urban, developed urban, and rural areas). Su et al. (2014) further visualized the nonstationary relationship between total ESs value and urbanization using a geographical weighted regression (GWR) model. Although these studies attempted to investigate interactions between ESs and urbanization, there are still some elements that have not yet been explored. First, clustering patterns between ESs and urbanization have been ignored, especially at the local scale. Spatial autocorrelations commonly arise between ESs and their drivers (including urbanization) (Baró et al., 2017; Xu et al., 2017), causing results obtained by ordinary least squares (OLS) and GWR to be biased to some extent. Therefore, other statistical techniques dealing with spatial autocorrelation must be employed. Second, previous studies have mainly focused on the regional scale and usually took administrative districts as the spatial unit. Analysis on this scale is underlain by a process aggregating locally collected data into meso- or macro-levels (e.g., town, county, and city); this level of analysis is thus unable to reflect local spatial variation. This may limit the practical applicability of ESs in local urban landscape planning.

As the biggest city in central China, Wuhan has experienced rapid urbanization since the early 2000s, which has caused remarkable change in the natural landscape and environmental deterioration (Ding et al., 2015). The government of Wuhan has made several landscape plans to mitigate the adverse effects of urbanization. A thorough understanding of the spatial relationship between ESs and urbanization will provide additional information for planning making. The aims of this study are: (1) to quantify and map ESs and urbanization using various models and multisource data; (2) to analyze spatial correlations between ESs and urbanization through the bivariate Moran's I and bivariate Local Moran's I methods; (3) to analyze the spatial dependence of ESs on urbanization through spatial regression models (SRMs), including the spatial lag model (SLM) and spatial error model (SEM).

2. Materials and methods

2.1. Study area

Wuhan City (29°58′–31°22′ N, 113°41′–115°05′ E) is in the middle reaches of the Yangtze River in central China, covering approximately 8569.15 km^2 (Fig. 1). It is situated in the transition regions between Jianghan Plain and Dabie Mountain, with flat plain terrain in the center and hill and ridge terrain in the north and south. The terrain is, by area, 5.8% low mountains, 12.3% hills, 42.6% ridge hillock plain, and 39.3% flat plain. The altitude is between 19.2 and 873.7 m, although below 50 m in most places. The climate is north subtropical monsoon (moist). The annual average temperature is 15.8–17.5 °C, annual total radiation is 104–-113 kcal cm^{-2}, and annual precipitation is 1150–1450 mm. Rivers, lakes, and ponds are widely distributed across the region, accounting for 2217.6 km^2, or 26.1%, of the whole area.

As the biggest city in central China and capital of Hubei Province, Wuhan has experienced a process of rapid urbanization since the early 21st century. Between 2000 and 2015, the population in Wuhan increased by 31.8%, from 8.05 to 10.61 million; the normal gross domestic product (GDP) increased 803.7%, from 120.68 to 1090.56 billion Chinese yuan; the actual GDP increased 557.2%; and built-up areas increased 94.3%, from 210 to 408 km^2 (data obtained from Wuhan Statistical Yearbook in 2000 and 2015). Administratively, Wuhan consists of 13 districts and 191 towns (or city communities). According to the latest spatial development plan, the region can be divided to four functional areas (Fig. 1): central urban area, functional urban area, new urban development area, and outer suburban area. By defining the spatial scope of different functional areas, this plan aims to guide the development of new urban areas and alleviate the pressures of population growth and industrial development on the urban center. In addition, this plan contributes to preventing disorderly urban expansion by delineating the spatial boundaries between urban and rural areas.

We chose Wuhan as our study area for the following reasons: (1) Wuhan has an abundance of natural habitats with high ecological value, which is not common in Chinese cities. Approximately half of the territory is covered by wetlands and forests, accounting for 39.54 and 11.4% of the total area, respectively. (2) Wuhan is the seventh most populous city in China, with an urban population of approximately 5 million. Urbanization in Wuhan has brought great challenges to its natural ecosystems. (3) Both regional and local authorities pay great attention to ecological protection and have initiated a series of successive landscape plans to prevent environmental deterioration, such as the Urban Growth Boundary (UGB) and Ecological Red Line (ERL) programs.