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Establishing an ecological vulnerability assessment indicator system for spatial recognition and management of ecologically vulnerable areas in highly urbanized regions: A case study of Shenzhen, China

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ABSTRACT

The extensive use of modeling and technologies such as a geographic information system (GIS) in ecological vulnerability assessment and the recognition of eco-environmentally vulnerable areas from the perspective of spatial positioning provide important complements to urban ecological space management research. This study establishes an ecological vulnerability assessment indicator system containing nine elements and twelve indicators with respect to ecological sensitivity, ecological pressure, and self-resilience. The range of ecologically vulnerable areas in a highly urbanized region is spatially recognized. Management strategies are proposed with regard to institutionalization and marketization. The results show that the ecological vulnerability in Shenzhen is good overall and that most areas are moderately vulnerable; the goal of space management is to enhance ecological function and prevent further expansion of the city as a threat to ecological security. Highly vulnerable areas are mainly distributed in the west and agglomerate with urban functional areas; it is suggested to delimit an ecological red line in this region and implement the most stringent "steel wire" control following the existing ecological protection law in China. Furthermore, this study proposes an ecological preparedness system suited for the particularity of the highly urbanized region in Shenzhen and attempts to introduce marketization into ecological restoration to solve the economic and social plight of ecological reconstruction in highly urbanized regions. The vulnerability assessment results objectively reflect the condition of the regional ecological environment, and the space management policy has implications for ecological protection, resource utilization, and sustainable development in similar cities.

1. Introduction

Urbanization is an important ecological challenge, and approximately 1/3 to 1/2 of the global land surface has been altered by human development activities (Vitousek et al., 1997). Since the 21st century, the international community has placed increasing emphasis on the concept of sustainable development. In particular, the range of the world's ecologically vulnerable areas has expanded, while the degree of ecological vulnerability has increased significantly. In 2006, the white paper "China's Ecological Protection" noted that ecologically vulnerable areas cover more than 60% of the national land area (State Environmental Protection Administration, 2006). There has been a trend to consider regional ecological vulnerability, spatially recognize ecologically vulnerable areas, and strengthen the effective management of the sustainable development of vulnerable areas when conducting regional ecological security research and constructing ecological civilization (Villa and McLeod, 2002).

The ecological vulnerability assessment, which originates from natural disaster research (Janssen et al., 2006), is an important means to recognize the ecological conditions in vulnerable areas. Ecological vulnerability has been considered a major research topic by the International Biological Program (IBP) in the 1960s, the Man and the Biosphere Program (MAB) in the 1970s, and the International Geosphere-Biosphere Program (IGBP) starting in the 1980s

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(Dow, 1992). Extensive research and discussion have been made on ecological environment systems at varying scales in different regions, typically using a vulnerability assessment in the scenario of global climate change (Kelly and Adger, 2000; Li and Tong, 2008; Cinner et al., 2013; Zhao and Wu, 2013). The first ecological vulnerability study performed in China dates back to the 1980s. In this study, the author used the ecological boundary theory and the technique of information measure to develop the index series which could be applied to determine the basic properties of ECOTONE (namely ecologically vulnerable areas) (Niu, 1989). Thereafter, this topic has received sustained attention, and the number of academic journal articles and master and doctoral theses per year in this field has shown a significant upward trend (Tian and Chang, 2012).

Ecological vulnerability is generally thought to be weak resistance and low resilience of ecosystems in response to external interference, including natural and artificial factors, at a specific spatial scale (Qiu et al., 2015; Beroya-Eitner, 2016). Despite the lack of a clear definition, researchers generally believe that ecological vulnerability is composed of components like exposure, sensitivity, and adaptive capacity (Turner et al., 2003; Adger, 2006; Li et al., 2008). Drawing inspiration from the United States public space planning integration framework, Polsky et al. developed the Vulnerability Scoping Diagram (VSD) evaluation integrated model based on "exposure–sensitivity–adaptive capacity". The VSD addresses vulnerability in three dimensions, namely, exposure, sensitivity and adaptive potential (Polsky et al., 2007). In accordance with the characteristics of Chinese cities, Qiao and colleagues provided a systematic elaboration on the concept of ecological vulnerability; they considered that ecological vulnerability is associated with the inherent ecological sensitivity and ecological resilience of the system as well as the ecological pressure it experiences. Further, this group established a conceptual model of ecological vulnerability assessment (Qiao et al., 2008). These methods are applicable at the municipal city level and are conducive to spatial correlation analysis between the evaluation results and natural geographic factors. Due to their high practical value, these methods have been used extensively (Li and Chen, 2014; Song et al., 2015).

On the whole, ecological vulnerability research has gradually evolved from mainly qualitative to comprehensive assessments that integrate natural, economic, social, cultural and environmental characteristics. However, existing studies have numerous limitations. Discrepancies between conceptual frameworks and evaluation models have become a major obstacle to the application of vulnerability assessment in decision-making. Many assessments fail to closely apply in practice. We propose that ecological vulnerability assessments should have clear objectives and that the assessment results should provide a reference for regional development and environmental remediation. This is also the fundamental goal and ultimate foothold of ecological assessments. Therefore, we performed an empirical study in the highly urbanized region of Shenzhen city in China, using a Geographic Information System (GIS) spatial analysis tool. We quantitatively revealed the spatial pattern of ecologically vulnerable areas in Shenzhen under the effects of multiple factors. Targeted spatial management measures were proposed to enrich the methodological system of ecosystem assessment and provide a reference for other cities and related research.

2. Methods

2.1. Study area

Shenzhen is located in the southern part of Guangdong Province, China. It is on the east coast of the Pearl River Delta adjacent to Hong Kong. The terrain declines from southeast to northwest. Most areas are low mountains, flat terraces, and terrace hills (Fig. 1). The total land area of Shenzhen is 1996 km^2. In 2014, the total area of construction land in this city was 968 km^2. The first special economic zone established during China's reform and opening, Shenzhen has created a remarkable "Shenzhen speed". In the past 30 years, Shenzhen has experienced large-scale, high-density urban population migration and agglomeration using much less time than "natural evolution". By the means of unified collection within the zone in 1992 and land conversion by urbanization out of the zone in 2004, Shenzhen became the first city without rural institution in China and achieved an urbanization rate of up to 100%. In 2014, the annual gross production reached 1.6 trillion Yuan, and the per capita GDP exceeded $20,000 in Shenzhen, which has long ranked first among China's major cities. The resident population grew from 300,000 in 1980 to 10.62 million in 2014.

Along with the rapid social and economic development in Shenzhen, urban construction land use continued to expand rapidly, and the total urban natural ecological space gradually decreased annually, exerting huge pressure on urban ecological resources. In 2005, Shenzhen delineated the first ecological control line in China (Fig. 1). Half of the city's land is included as ecological conservation land within the ecological line. In this study, we assessed the land within the ecological line; the land outside of the line, namely, construction-activity space, was defined as a non-vulnerable area.

2.2. Methodology

The concepts of sensitivity, responsiveness, resilience, and adaptive capacity have become major components of vulnerability (De Lange et al., 2010; Ippolito et al., 2010; Constantin et al., 2015). A methodology to map ecological vulnerability to fire was proposed in natural protected areas of Torre Guaceto (Aretano et al., 2015; Semeraro et al., 2016), and the suitable indicators allow discriminating different levels of sensitivity (e.g. Habitat relevance, Fragmentation) and stresses (e.g. agriculture field, road infrastructures). Moreover, the result provides evidence of its potential usefulness for the effective management and the vulnerability models are included in the well-known European Driver-Pressure-State-Impact-Response (DPSIR) framework (European Environmental Agency. (EEA), 1999).

In this study, we consider that the inherent sensitivity of the ecological environment is a potential condition leading to ecological vulnerability; resilience enables the ecosystems to withstand the interference and still maintain its basic structure and function under certain conditions; ecological pressure ultimately stimulates and results in the manifestation of various vulnerability factors in the ecosystem. If there is no high-intensity ecological pressure, an ecological environment with high ecological sensitivity and resilience may evolve in a better direction and make it difficult for the vulnerability to emerge. Compared with similar studies, an integrated assessment of sensitivity, resilience and pressure can help guarantee a comprehensive understanding of the vulnerability of a regional ecological environment (Table 1).

Ecological sensitivity is used to measure and describe the instability of an ecological environment and is a potential vulnerability factor in an ecosystem (Luers et al., 2003). Major ecological problems in Shenzhen include a decrease in natural forest area, a decline in soil and water conservation capacity, and a reduction in biodiversity. Geological disasters, such as seawater intrusion, emerged in the late 1970s, leading to deterioration of the geological environment. Considering the major ecological problems and characteristics of Shenzhen, we chose soil condition, habitat condition, and geological condition to characterize the ecological sensitivity.

Ecological resilience, namely, the self-regulation and restorability of an ecosystem, depends on the vegetation, topography,