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Research Paper

Assessing urban landscape ecological risk through an adaptive cycle framework

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A R T I C L E I N F O

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A B S T R A C T

Cities are suffering various ecological risks due to rapid urbanization and global climate change. Urban landscape ecological risk assessment is conducive to identifying high risk areas and guiding risk prevention. However, few studies have characterized the dynamic processes of landscape ecological risk. In this study, taking Beijing City as a case study, the adaptive cycle in resilience theory was incorporated into a risk assessment framework using such three criteria as potential, connectedness, and resilience, together with integrating exposure and disturbance effects of risk sources. This framework contributed to understanding the complex interactions between landscapes and risk effects from a holistic and dynamic view. The results showed that the ecological risk of "potential" and "connectedness" weakened radially from downtowns to outer suburbs. The distributions of "resilience", "exposure", "disturbance", and the final risk, all exhibited a concentric pattern of the higher risk, highest risk, and lowest risk sequentially from downtowns to outer suburbs. The results reflected the facts that residents living in downtowns had taken ecological restoration measures to reduce risk, while continuous urban constructions in outer suburbs increased the risk. In terms of the adaptive cycle phases of ecological risk, Yanqing, Miyun, Huairou, Mentougou, Fangshan and Pinggu districts were in the reorganization α-phase; Daxing, Changping, Shunyi and Tongzhou districts were in the exploitation r-phase; Dongcheng, Xicheng, Fengtai, Haidian, Chaoyang and Shijingshan districts were in the conservation K-phase. The results provided scientifically spatial guidance for implementing resilient urban planning, in order to realize sustainable development of metropolitan areas.

1. Introduction

Natural ecosystem is a significant basis for human survival and development. However, global climate change and rapid urbanization have exacerbated ecological risks and affected social sustainability (Estoque & Murayama, 2014). The U.S. Environmental Protection Agency defined ecological risk as the likelihood that adverse ecological effects would occur when an ecosystem and its components were exposed to multiple risk sources (USEPA, 1998). Ecological risk assessment is the prerequisite for risk control, and contributes to supporting environmental decision-making (Piet et al., 2017). In recent studies, ecological risk sources have extended from a single biochemical factor (Tarazona, 2013), to diverse sources caused by human activities and natural hazards (Van den Brink et al., 2016). In addition, risk receptors have also extended from ecosystems to systems coupling human and nature (Paukert, Pitts, Whittier, & Olden, 2011).

Urban ecological risks are characteristic of multi-source and multi-receptor influences with complex exposure and disturbance mechanisms. Most previous studies on urban ecological risk assessment discussed the effects of natural disasters such as geological changes (Carreño, Cardona, & Barbat, 2012) and flood hazards (Camarasa-Belmonte & Soriano-García, 2012). Given the complexity of urban ecological risks, the research trend of risk assessment is to characterize the spatial and temporal heterogeneity of risk sources and receptors, and risk effects in an interrelated perspective (Li, Kappas, & Li, 2017). The introduction of landscape ecology into the list of considerations follows this trend. Landscape ecological risk assessment (LERA) takes the landscape, the heterogeneous mosaics consisting of social and ecological systems, as the evaluation object. The traditional ecological risk assessment emphasizes on overlapping multiple risk sources to characterize risk patterns in a region, LERA focuses on spatializing the effects and responses of landscape to risk sources under the background

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of correlations among landscape patterns and ecological processes (Peng, Dang, Liu, Zong, & Hu, 2015).

At present, urban LERA is still in its infancy. Chinese scholars have put forward landscape ecological risk indices based on ecological vulnerability and disturbance indices (Mo, Wang, Zhang, & Zhuang, 2017). Such methods described the static pattern of ecological risk rather than the dynamic process of risk adaptation and interaction. However, if a region with low ecological risk exhibits an increasing trend of risk in the time series, it cannot be concluded the region is experiencing good environmental conditions. In this context, it is necessary to consider the city as a "living" adaptive system when applying LERA in urban environmental management.

The theory of resilience has emerged as a dynamic approach to analyzing how a system can deal with risks. Resilience is a concept originated from physics (Resnick & Taliaferro, 2011). Holling (1973) firstly introduced resilience in the field of ecology and defined it as the capacity of a system to absorb disturbance and remain essentially in the same state. Along with the introduction of socio-ecological systems (SESs), resilience theory is being perfected gradually (Adger, 2000). SESs are complex adaptive systems composed of human and nature, which have the major characteristics of historical dependency, nonlinearity, threshold effects, multiple stable states, self-organization, and limited predictability (Cumming et al., 2005). Resilience theory provides a more realistic viewpoint of enhancing the capacity of SESs to adapt to surprise and uncertainty (Lei, Wang, Yue, Zhou, & Yin, 2014).

The adaptive cycle is a key heuristic model within resilience theory and has been used to analyze the evolution of SESs (Burkhard, Fath, & Müller, 2011). The adaptive cycle describes such four sequential phases as exploitation (r), conservation (K), release (Ω), and reorganization (α) involving three changing features of potential, connectedness and resilience (Gotts, 2007). The feature of potential represents the accumulated capitals in systems, while for the feature of connectedness it encompasses the quantity and frequency of interactions among components (Grundmann, Ehlers, & Uckert, 2011). When affected by multiple risk sources, SESs resist and adapt to the risk effects in order to restore or maintain the stable states, which drive the evolution of the adaptive cycle (Walker, Gunderson, Kinzig, & Folke, 2006). The adaptive cycle has been applied to explore sustainable development of SESs under the background of global environmental change (Müller et al., 2015). With the maturity of resilience theory, the applications of adaptive cycle have mainly included two aspects. Firstly, a variety of case studies have explored the adaptability and transformability in complex systems such as agricultural systems (Rawluk & Curtis, 2016) and coastal zones (Angeler et al., 2015). Secondly, resilience theory has been applied to urban systems to develop a new concept, the resilient city, which has gradually penetrated into the theory and practice of urban planning and design since the 1990s (Meerow, Newell, & Stults, 2016). Furthermore, the concept of resilient city is integral to achieve the sustainable development of communities or cities (Sharifi, 2016).

Identification and assessment of landscape ecological risks are important for resilient city planning. Liu, Wang, Peng, Zhang, & Wei (2015) introduced a three-dimensional (3-D) adaptive cycle framework that integrated dynamic resilience factors into the risk assessment index system, which enriched the methodology of LERA. Nonetheless, their study did not further analyze the relationship between ecological risk and the adaptive cycle. In this study, urban adaptive cycle is thought to be driven by the interactions among ecological risk effects and urban landscape. When exposed to or disturbed by risk sources, urban landscape will respond in the change of landscape units, landscape structures and landscape processes, respectively corresponding to the interrelated features of potential, connectedness and resilience. Thus, a 3-D indicator system based on the "potential", "connectedness" and "resilience" criteria can be developed for LERA focusing on the adaptive phases of landscape ecological risk.

Beijing City has become one of the most representative metropolitan areas with rapid urbanization in China. The contradictions between environmental protection and urban development are increasingly apparent. Natural disasters such as heat wave, soil erosion, waterlogging have seriously affected the health of urban residents and natural ecosystems. Thus, there is an urgent need for LERA to encourage the city to actively adaptive against ecological risks and look for new paths of urban development. Taking Beijing City as a case study area, this study is aimed to propose a 3-D indicator system for LERA, to identify the adaptive phases of urban landscape ecological risk, and to put forward spatial planning strategies of districts at different phases in the view of resilient city planning.

2. Materials and methods

2.1. Study area and data sources

Beijing City is located at the northern tip of the North China Plain, with a total area of 16,410 km^2. It is surrounded by Hebei Province except where it is adjacent to Tianjin City in the southeast. Beijing City comprises 16 administrative county-level subdivisions, including two downtowns (Dongcheng and Xicheng districts), four suburbs (Chaoyang, Haidian, Fengtai and Shijingshan districts), and ten outer suburbs (Changping, Fangshan, Mentougou, Shunyi, Tongzhou, Daxing, Yanqing, Huairou, Miyun and Pinggu districts). Approximately 38% of Beijing's terrain is flat (in the east and south) and 62% is mountainous (in the north and west) (Fig. 1). Beijing City belongs to the warm temperate zone with the half-moist continental monsoon climate. The annual average temperature is approximately 10–12 °C and the annual precipitation is about 644 mm.

As the capital of China, Beijing City is the political, economic and cultural center of the country and has already developed into a typical metropolitan area. According to the statistical data for 2016, Beijing City had a total population of nearly 22 million and an urbanization rate of 86.5%. Along with the rapid socio-economic development, excessive population and industrial agglomeration, and uncontrolled spread of urban construction land have resulted in air pollution, soil erosion, soil pollution, urban heat island and other eco-environmental degradations in recent years. These problems seriously threaten regional ecological security and residential environmental quality in Beijing City.

In this study, the required data to calculate the indicators for LERA included remote sensing imagery, vegetation and terrain data, meteorological data and nighttime lights data. The data sources are listed in Table 1.

2.2. Conceptual framework

LERA takes the landscape as evaluation object. Landscape is regarded as the interrelated social and ecological system from a comprehensive and holistic view (Li, 2000). The effects of ecological risk may occur when landscapes are exposed to or disturbed by ecological risk sources, and the responses of SESs will trigger further changes in landscapes (Bauch, Sigdel, Pharaon, & Anand, 2016). These changes will show different characteristics in landscape patterns and processes at various spatial and temporal scales. The adaptive cycle, a heuristic model within resilience theory, provides a holistic and dynamic approach to understanding the complex interactions between landscapes and risk effects (Folke, Carpenter, Walker, & Scheffer, 2010; Ingalls & Stedman, 2016).

From a landscape perspective, the "adaptive" emphasizes on the capacity of adaptability, resilience, and transformability of the landscapes responding to risk effects (Walker, Holling, Carpenter, & Kinzig, 2004). The "cycle" articulates that landscapes can adapt against risk effects and move through the cyclic phases of exploitation (r), conservation (K), release (Ω) and reorganization (α), with changes in three interrelated features, i.e. potential, connectedness, and resilience (Bunce, Mee, Rodwell, & Gibb, 2009; Gotts, 2007; Gunderson &