Science of the Total Environment 574 (2017) 1000–1011

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Impacts of road network expansion on landscape ecological risk in a megacity, China: A case study of Beijing

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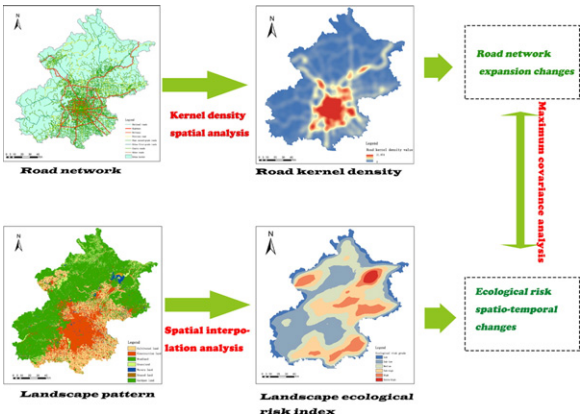
HIGHLIGHT

- The kernel density estimation based on GIS characterized the expansion of road network effectively.
- Constructing the landscape ecological risk index with landscape indices.
- Both the road network expansion and the ecological risk changes had close relations to expressways in space.
- The maximum covariance analysis was used to explore the affecting laws of road network on regional ecological risk.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 11 May 2016
Received in revised form 6 September 2016
Accepted 6 September 2016
Available online 14 October 2016

Editor: D. Barcelo

Keywords:
Road network
Landscape ecological risk
Kernel density spatial analysis
Beijing

ABSTRACT

Road networks affect the spatial structure of urban landscapes, and with continuous expansion, it will also exert more widespread influences on the regional ecological environment. With the support of geographic information system (GIS) technology, based on the application of various spatial analysis methods, this study analyzed the spatiotemporal changes of road networks and landscape ecological risk in the research area of Beijing to explore the impacts of road network expansion on ecological risk in the urban landscape. The results showed the following: 1) In the dynamic processes of change in the overall landscape pattern, the changing differences in landscape indices of various landscape types were obvious and were primarily related to land-use type. 2) For the changes in a time series, the expansion of the road kernel area was consistent with the extension of the sub-low-risk area in the urban center, but some differences were observed during different stages of development. 3) For the spatial position, the expanding changes in the road kernel area were consistent with the grade changes of the urban central ecological risk, primarily because both had a certain spatial correlation with the expressways. 4) The influence of road network expansion on the ecological risk in the study area had obvious spatial differences, which may be closely associated with the distribution of ecosystem types.

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http://dx.doi.org/10.1016/j.scitotenv.2016.09.048

1. Introduction

The road network is a product of urban development processes, and it plays a role in urban economic development. Additionally, a road network has many influences on ecological processes within the urban landscape. On one hand, a road network affects material cycles, energy and information communication in human societies and in addition to reducing the cost of transportation, a road network also expands the scope of human activities (Forman and Alexander, 1998). On the other hand, road networks also cause various adverse effects, including division, interference, damage, and pollution (Forman and Alexander, 1998; Karlson et al., 2014), which directly or indirectly affect ecological processes and accelerate habitat destruction and ecosystem degradation, eventually leading to an increase in regional ecological risk. Landscape ecological risk is an important branch of ecological risk at the regional scale and primarily depends on the coupling of landscape patterns and ecological processes to achieve integrated characterization of multi-source risks from natural or human activities (Simmons et al., 2007; Li and Zhou, 2015). Because of the complexity of human activities and their effects on ecological processes, the influences of road network expansion on regional ecological risk are also diverse. These influences include changes in regional biodiversity and in the transfer of energy and materials among ecological systems (Barandica et al., 2014; Staab et al., 2015), in addition to changes in land-use and the evolution of landscape patterns (Patarasuk et al., 2012; Xie et al., 2016). The evolution of forest landscapes over time and the spatial separation of water areas are also affected (Freitas et al., 2012; Du et al., 2010). By studying these processes, researchers have made progress in their research and have constantly deepened the understanding of the mutual relations between road network expansion and ecological risk. For example, the studies on road network structure include either a single main road or a complex road network (Fan et al., 2011; Redon et al., 2015), and study areas include small regions with little interference from human activities, such as forests, and areas that are greatly affected by human activities, such as cities and large basins (Narayanaraj et al., 2012; Xie et al., 2016; Barber and Cochrane, 2014). Additionally, research contexts include the influence of road networks on regional landscape ecological risk (Liu et al., 2008), using ecological risk assessment for guidance in the construction and planning of the road networks (Cao et al., 2010), and some other aspects (Staab et al., 2015). However, because of the complexity of the study areas and the diversity of ecological research methods, most studies focus on landscape ecological risk assessment (Huang et al., 2016; Bian et al., 2015; Liu et al., 2016), and studies of changes in the spatial characteristics of road networks are rare.

A road network is a complex network system with certain spatial features that is gradually formed by a few roads in a region through long-term planning and development. It also stands for the urban development level, especially Beijing—a city with extra high urbanization level. In the process of urbanization, the road network expansion exerts extensive and profound influences on regional ecological systems (Tian et al., 2016). On one hand, the ecological effects of road networks will continually increase over time. With the continuous concentration of the population, the natural environment surrounding roads has been severely damaged, resulting in a weakened ability of regional ecosystems to resist external risks and increases in ecological risks (Liu et al., 2008). On the other hand, the scope of influence of road networks will further enlarge in the process of expansion (Coffin, 2007). With improvements in road systems, the range of human activities also expands, which increases the human impact on the natural ecology (Forman and Alexander, 1998; Karlson et al., 2015). According to some research, approximately 15–20% of the U.S. total geography is land affected by road networks (Forman, 2000) and about 16% of the Netherlands is covered by road effect zones (Reijnen et al., 1997).And In China, the affected area reached 18.37% (Li et al., 2004). However, the development of the regional economy cannot leave the extension of the road network, but the ecological effects caused by the road network expansion cannot be ignored. Facing the increasingly prominent contradiction between economic development and ecological protection, people urgently need to find a scientific way to solve the problem. Therefore, studying the road network expansion and its impacts on the ecological risk in Beijing as the study area, this study can provide important references for city in road network planning and ecological management. Meanwhile, the study also has important value to further understand the effects of road networks on landscape ecological risk (Liu et al., 2008; Eigenbrod et al., 2009; Karlson et al., 2014).

It's worth noticed that, in recent years, with the rapid development of spatial information technology, the research methods of geography have been used in a wide range of applications in various fields, particularly in the development of the geographic information system (GIS). GIS is used to solve many questions about transportation and the environment with various methods of spatial analysis (Guo et al., 2014; Chang et al., 2015; Hu et al., 2016). Among these methods, the kernel density estimation, an important spatial analysis tool based on geographic information systems, offers a powerful method of analysis to study the effects of road network expansion on landscape ecological risk by addressing the limitations of classical road density at different scales effectively. Kernel density spatial analysis is an important spatial analysis tool based on the combination of the nonparametric estimation of kernel density and geographic information systems (Liu et al., 2011; Cai et al., 2012; Anderson, 2009). To reflect the spatial differences of the road network density in the study process, according to the values of kernel density, we defined the values within a certain range as a "kernel" in space. According to the size of the kernel area or the sequence of the kernel generation, the kernels were classified as main kernels, subkernels, old kernels, or new kernels, which intuitively characterized the expansion processes of the regional road network (Liu et al., 2011; Xie and & Yan, 2008).

The aim of this study was to explore the road network expansion changes in Beijing and its impact on landscape ecological risk. For the purpose, with the support of geographic information technology (GIS), by applying the kernel density estimation tool, the road network density in Beijing was derived and an ecological risk index was constructed based on the landscape indices. Then, we analyzed changes in the road network and the landscape ecological risk by time–space evolution analysis to reveal the effects of road network expansion on regional landscape ecological risk.

2. Materials and methods

2.1. Study area

Beijing is located on the eastern coast of China (115.7°–117.4° E, 39.4°–41.6° N) and has 14 districts and 2 counties for a total area of 16,410.54 km^2. Since 2005, the government has led the establishment of the city's development model, and all of the districts and counties were classified into four large functional districts to support sustainable development: the capital core district (Inner city), the urban functional extension district, the new urban development district, and the ecological conservation district (Fig. 1). The capital core district and the urban functional extension district were primarily based on an artificial greenland ecosystem; most of the farmland ecosystems were located in the new urban development district and these areas were seen as the urban outskirts; and the woodland and grassland ecosystems were primarily distributed in the mountains of the ecological conservation district, which were took as the urban suburban. The entire city is surrounded by mountains in the west, north and northeast and to the southeast, is the Beijing plain. Depended on the flat terrain, the road network system in the middle of city is extremely developed. The urban road network uses the loop line as the backbone, with successively built urban expressways from two-ring to six-ring. The other primary trunk roads form a spatial pattern that radiates outward from the urban center, and they connect the internal and external branches of the loop