Ecological Indicators 96 (2019) 392–403

Contents lists available at ScienceDirect

Ecological Indicators

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

Original Articles

Spatial variations in the relationships between road network and landscape ecological risks in the highest forest coverage region of China

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ARTICLE INFO

Keywords:
Landscape ecological risk
Road network
Kernel density estimation
Geographically weighted regression
The Minjiang River

ABSTRACT

The road network is one of the most ubiquitous and significant long-term legacies of all types of human disturbances on the landscape. Taking the upper reaches of the Minjiang River in Fujian Province of southeast China as a case, the spatiotemporal dynamics of the landscape patterns and landscape ecological risk (LER) were explored, and based on the geographically weighted regression (GWR) model, the geographical heterogeneity in the correlations between the road network and the LER were identified. Our results showed that: (1) The distribution of the LER had a gradually decreasing trend from the middle to the periphery in 2007, with the high-risk area expanding to the western part of the study area in 2012 and 2016. The LER close to the road network was generally higher than those far from the road network. (2) The GWR model fit our case better than the ordinary least square (OLS) model, with both of the measurements of the road network (i.e., distance to the nearest road, DNR; and kernel density estimation, KDE) being significantly correlated with the LER at the 1% level. (3) According to the quantified coefficients estimated by the GWR model, we found that there were spatial variations in the associations between the two regressors and different level effects of roads on the LER. (4) The GWR analysis also indicated that the high-level roads mainly affected areas where human activities were more intensive, whereas the low-level roads infiltrated every corner of the region, mainly affecting areas that were far from the city. (5) The significant cumulative impacts of the road network on the LER were also observed in this study. Benefitting from the quantification and visualization of the spatial paradigm in regard to their trade-off and the synergistic associations between the LER and the road network at the grid level, our study provides suggestions for implementing more appropriate policies that will alleviate the impact of road construction on the landscape. This study also sheds light on further applications of the GWR model in future research on road ecology.

1. Introduction

Ecological risks reflect the possibility that an ecosystem will be confronted with a degrading response to external disturbances (Gong et al., 2015). One of its major branches is landscape ecological risk (LER). The magnitude of LER is affected by multi-source threats from both natural and human interferences, such as agricultural and forestry practices and road network extension, which can be observed by the integrated trait of both landscape patterns and ecological processes at the regional scale (Li and Zhou, 2015; Simmons et al., 2007). The road network is among the most prevalent of all the types of human disturbances (Forman et al., 2002; Valipour, 2015), and its increasing influence on natural ecosystems has been observed over the past two decades (Coffin, 2007; Karlson and Mortberg, 2015; Selva et al., 2011). According to previous studies, nearly 15–20% of the total land is covered by the road effect zone in the USA (Forman, 2000), approximately 16% in the Netherlands (Reijnen et al., 1997), and this number is approximately 18.37% in China (Li et al., 2004). The road network will directly or indirectly accelerate the fragmentation and degradation of a habitat, eventually resulting in an increase of LER (Freitas et al., 2012; Barandica et al., 2014; Staab et al., 2015). With a sharp increase in the contradiction between the road network and ecological resources protection, it is important to better understand their relationships to find scientific methods to pursue sustainable development.

In recent years, evaluations of LER have drawn wide attention around the world (Ayre and Landis, 2012; Li et al., 2017; Peng et al.,

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https://doi.org/10.1016/j.ecolind.2018.09.016
Received 2 April 2018; Received in revised form 6 September 2018; Accepted 9 September 2018
1470-160X/

2015). These studies provide an important contribution to the understanding of the effects of human disturbances on the ecosystem (Li and Huang, 2015; Xu and Kang, 2017; Zhou et al., 2014). Meanwhile, the effects of road construction on landscape sustainability have also been extensively investigated at various levels, including a single road, a certain level of roads or even a complicated road network (Barber et al., 2014; Hu et al., 2016; Narayanaraj and Wimberly, 2012). However, most of these studies concerning the effect of roads tend to focus on analysing the patterns of landscapes (Liu et al., 2014; Redon et al., 2015); few studies have performed a LER assessment associated with the road network; in particular, spatial variations in the relationships between the road network and LER across locations have not yet been reported (Mo et al., 2017).

The road network, which enhances the attraction and radiation of the manmade landscape, has become a focus of landscape research over the past two decades (Hawbaker et al., 2006). Along with long-term planning and the development of roads in a region, a complex network system with certain spatial characteristics has gradually formed. To observe the ecological effects of a road network, the spatial pattern of the road network should be quantified first (Cai et al., 2013; Mo et al., 2017). Road density (RD) is one of the most commonly used indices that can effectively characterize the features of a road network. Due to the rapid development of geographic information systems (GIS), its spatial analysis tools have been used extensively in various fields, including road ecology studies (Hu et al., 2014; Karlson et al., 2014; Vu et al., 2013). Among these spatial analysis tools based on ArcGIS, kernel density estimation (KDE) (Parzen, 1962), which is a spatial analysis method that measures the density of the road network, offers a powerful tool for quantifying the spatial features of a road network. KDE has been employed to observe the ecological impacts of the road network and has proven to be an effective measurement in its joint consideration of both the spatial configuration and the function of a road network (Anderson, 2009; Cai et al., 2013; Hu et al., 2017). Buffer analysis (BA) and distance to the nearest road (DNR) are also effective methods employed in many road impact analyses; for example, researchers have used the DNR index to analyse the impacts of the road network on the changes in forest cover (Hu et al., 2014; Chaudhuri and Clarke, 2015; Hu et al., 2016) and have used the BA index to explore the impacts of road network extensions on landscape patterns (Liu et al., 2014; Liang et al., 2014).

As mentioned above, the spatial distribution of a road network characterized by the indicators of RD, KDE, and DNR constrains the rates and pathways of LER changes. However, how much these variables are able to explain the patterns of LER is still uncertain. The OLS technique has been used to explore the effects of human interference factors on the landscape in many of previous studies; for example, the linear regression model was used to study urban landscape changes (Seto and Kaufmann, 2003), the multinomial logistic model was applied to explore the forces of forest landscape change (Poudyal et al., 2008), and the maximum covariance analysis was applied to analyse the impact of the road network on LER (Mo et al., 2017). However, the OLS may ignore the spatial non-stationarity of geographical factors (i.e., LER) and lead to biased outcomes or inefficient estimations (Austin, 2007; Valipour, 2015) because the relationships between road indicators and LER may vary greatly across a study area. In this context, the geographically weighted regression (GWR) model was proposed (Fotheringham et al., 2002) to identify the geographical variation in the relationship between two regressors at the pixel level. The GWR model has been extensively used to explore the driving patterns in land use and cover changes (Buyantuyev and Wu, 2010; Giri and Qiu, 2016; Tu, 2011), forest landscape dynamics (Hou et al., 2015; Pineda Jaimes et al., 2010), and other ecological and environmental process (Hu et al., 2015; Mulley et al., 2016; Zhang et al., 2016). The GWR model has been proven to be an effective solution to evaluate the spatial non-stationarity and thus overcome the problem produced by OLS models. Therefore, in this study, the GWR model was employed to explore the impact of different dimensions of road networks on LER.

Fujian Province, which is located on the southeast coast of China, has the highest forest coverage rate in the country (Ren et al., 2011). Sanming City possesses the highest vegetation coverage in the province and is one of the major areas in China in terms of the forest production industry. However, the region is experiencing active transformations among landscape types caused by the combination of nature and human activities (Zhang et al., 2010). Furthermore, the road network of Sanming City has expanded rapidly over the past 30 years (Hu et al., 2017). The significant alteration of the forest landscape by the extension of the road network has potentially negative effects on biodiversity conservation and habitat loss, thus leading to an increase of the LER. Therefore, identification and quantification of LER associated with road network development are of great value for this region. Meanwhile, this study will provide an important theoretical basis and methodology for road network planning in other regions to alleviate its impact on the ecosystem.

Taking Sanming City as a case, the aim of this study was to fill in the knowledge gap of spatial variation in the association between the road network and LER. For this purpose, we initially introduced the GWR model to analyse the spatial paradigm in their associations. Specifically, the objectives were to: (1) quantify and visualize the spatio-temporal distributions of the landscape pattern and LER in different periods; (2) identify the spatial variation of the effects (both sign and size) of the road network on the LER by applying GWR models at the grid level, with the LER index as a dependent variable and the KDE and DNR of different level roads as well as topography indicators (i.e., slope and elevation) as independent variables.

2. Materials and methods

2.1. Study area

Sanming City (116°22′–118°39′E, 25°30′–27°07′N), including the Sanyuan District and Meilie District, is located in the western part of Fujian Province in China. Sanming City is in the upper reaches of the Minjiang River, which has the seventh highest annual runoff in China. The study area has a total area of 115 815 hm^2, and most of its lands are mountainous areas with steep slopes. The climate is generally mild and moist, with an annual average relative humidity of 78.3% and an average temperature of 19.55 °C. The annual average precipitation is 1665.3 mm, most of which occurred during the period of March to August (Yang et al., 2007). In the study area, the forest is the predominant landscape, constituting of more than 80% of the land use. Thus, it was labelled as the most "green" city in the most "green" province of China.

Sanming City was chosen as the case study here for two reasons. First, Sanming City is located in the middle subtropical zone, where the North-South subtropical flora meets, with complex terrain, rich wildlife and lush vegetation. At the same time, it was also one of the refuges for plants during the Quaternary glacial period in China, thus preserving many valuable prehistoric "relic plants"; e.g., there are near 700 hm^2 secondary forest of *Castanopsis kawakamii* in the study area, which is among the largest in the world. It has been reported that the forest has experienced increasing artificial interference in recent decades (Hu et al., 2014). Second, the study area has vigorously developed transportation in recent years and will in the future to promote the development of eco-tourism and other related industries. The significant alteration of the forest landscape by the extension of the road network has potentially negative effects for biodiversity conservation and habitat loss, thus leading to the increase of LER. How to deal with the harmonious relationship between the road network extension and ecological protection is a key scientific issue for the study area and elsewhere in the world. Thus, our results will have a good policy implication for biodiversity and habitat protection, and the method applied here (i.e., the LER index and the local model) have a good