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Characterizing the hierarchy of road network and its landscape effect with graph theory*

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Abstract Roads are conspicuous components of landscapes and play a substantial role in defining landscape pattern. Previous studies have demonstrated the link between roads and their effects on ecological processes and landscape patterns. Less understood is the relationship between landscape patterns imposed by the network in relation to road network configuration, spatial heterogeneity etc. Our hypothesis was that effect of road network on landscape patterns can be explained in relation to graph theoretical indexes describing the network features and landscape patterns. Taking Lancang River Valley in Southwest China as a case, we examined the road network features of different road grades and the landscape pattern variability at county scale. The results showed that the indexes of road network, such as corridor density, α circuitry index, β line-node ratio, and γ connectivity index, varied greatly at county scale in Lancang River valley. Road density has a positive relation with road corridor number, α connectivity index, β line-node ratio, and γ circuitry index. Patch density and average patch area (1980, 2000) have a significantly positive relationship with α, β, γ indexes which suggest landscape fragmentation was intensified with the network extension.

Keywords road network; landscape effect; graph theory; Lancang River

1 Introduction

Networks are objective phenomena in the natural and social system and follow certain rules [1]. In the abstract, network was formed by a certain number of nodes and corridors which connect the nodes. In reality, road system can be seen as an entity of network as it has hierarchy nodes, corridor and certain spatial pattern [2]. The city, town and village the road cross can be seen as nodes and different road types formed road network [3].

The expansion of road networks accelerate regional economy while also affect ecosystems at different scales. The direct or indirect influences of road can extend from population to landscape level. Road network is inherent corridor of human activities and the activities within a landscape often result in and use conversion, loss of land cover types, and fragmentation of remaining land cover into smaller and more isolated elements. So, road development is a primary mechanism of fragmentation, removing original land cover, creating edge habitat, altering landscape structure and function, and increasing access for

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humans [4]. Little research has been carried out at landscape scale, especially effect of different road type and network on ecosystems [5, 6].

The network analysis with graph theory was widely used in the geography mainly in the aspect of transportation, commerce site selection, etc, while little information in the ecological effect [7]. Also, to some extent, ecological impacts of roads may have underestimated because road data usually do not include the full road network. Less understood is the landscape pattern imposed by different roads classes [8].

Recent several decades, China experiences fast-speed road construction especially high-level road and the effects of road networks cause more and more attraction. During the policy of "West development", many high-grade roads were constructed. We take Lancang River Valley in Southwest China as study region and to elucidate the road network characteristics using graph theory, and finding the relationship between landscape pattern variability and the road network features. We hoped that the results presented would provide insight into road management and regional ecosystem conservation.

2 Methods

2.1 Study Area

Lancang River Valley which is a junction of Southwest China and Southeast Asia, is quite well known for great biological diversity and complex ecosystems [9]. The valley includes 39 counties. Highway accounts for more than 90% road transportation. It is representative region to study the road effect for particular natural environment and intensifying human disturbance there [8]. In recent years, human disturbance increases and road network grows rapidly with tourism development and major engineering projects such as hydroelectric station, expressway construction.

2.2 Sources of Data

The road vector data in this study were digitized using present status and transportation plan map of Yunnan province in 2000 and also acquired by 1:250000 road databases from national fundamental geographical information centre in 2000. Ecosystem types were classified by TM image in 1985 and 2000 [3].

2.3 Network analysis

Our study was carried out on county scale. Within the valley, we calculated landscape metrics for each vegetation quads. We examined the features of network configuration by grouping roads into five combinations according to road class: class I, classes I-II,I-III, I-IV, and I-V.

Road network structure can be described by three landscape indices: α index (Network circuitry, the loop percentage in the network), β index (Edge-nodes ratio, average linage of each node), γ index (Network connectivity, per cent connectiveness)[10]. The statistical indexes are useful in calculating a network efficiency and connectivity [11,12]

3 Results

3.1 Road network features and its heterogeneity in Lancang River

In graph theory, the topology structure of network includes regular network, random network, and complex network (mainly non-scale network)[13]. Evidently, road network is not regular network. Also, scientist found that most network in reality is neither regular nor random network. The actual network which named as complex network has special statistic features unlike the above two networks. The most important characteristics are small-world effect and non character scale[14,15]. Most road networks are dynamic and open system and results of random and regular outside force. From table 1, we can conclude that road network accords more with non-scale network.

Table 1: The contrast of stochastic and non-scale networks[7]

Parameters compared	Random network	Non-scale network
Node distribution	Poisson	Power-law distribution
Character scale	Average	No character scale
Average distance	Small	Small
Network cluster ratio	Small	Large
Axial node	Nonexistence	Exist minority

In Lancang River valley, there exist great topographical variations and the physiognomy includes mountains, hill, plain etc. Also, the ecosystems and the land uses are very diverse such as forest, farmland, grassland, water, town, and city etc. The combinations of topography and land uses also affect the road network forms. Generally, from the formation, development, and interaction, road network generation and development can be divided into five stages: homogeneous space → point status → line status → branching status → network status spatially [16]. Below are some representative examples in the Lancang River valley. The road form in Fig.1 (a) is mostly found at smaller scale between two villages. Fig.1(b) is a branch of Fig.1(c) and they exist in the mountainous areas. Fig. (d) often exist in the lake-circling or city-circling roads. Fig.(f) is a common shape in the plain or little hill region.

3.2 Road network analysis in Lancang River Valley

3.2.1 Relationship between the network features and road density

We used road density as independent variables and road corridor density, the α, β, γ index of road network as dependent variables. The relationships were shown in Figure 2.

Road network structure can reflect road ecological effect. α, β, γ index can indicate the network integration and complex and contain more information than road corridor indices especially at landscape and regional scale. The study focused on the regularity of the inherent relations and the actual values and variation of indices of different counties was not further discussed. The network analysis based on graph theory were used to network features and its optimization and put forward quantitative results abstracting the complex real road or other systems to simple "graph" shape. Also the indices are designed to measure fairly abstract attributes. The α circuitry index showed the loop percentage in the network. The β index indicates the complexity of the network. The γ ratio represents the percent of connectiveness within each network. The larger the α value is, the more

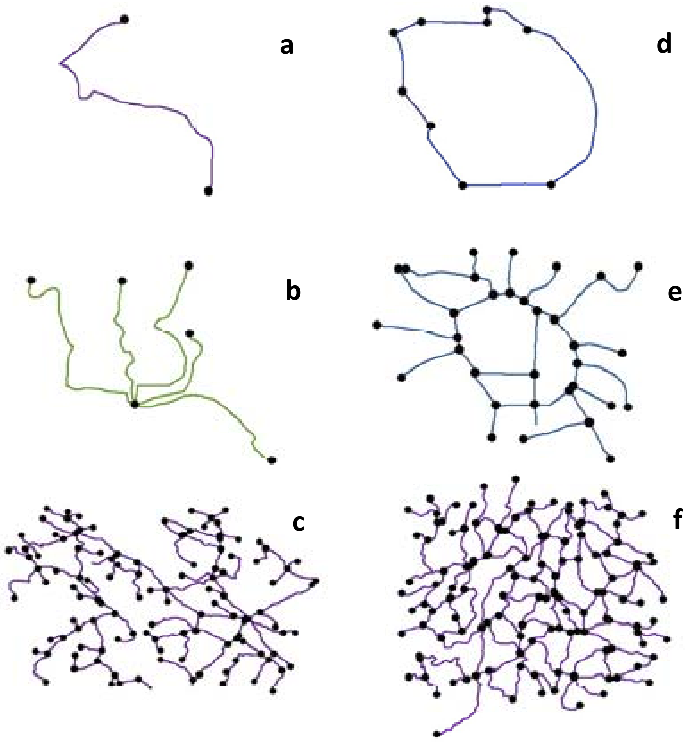

Figure 1: Examples of the road networks in Lancang River valley.

circuits the network has. The network has no circuit when α=0 and utmost circuit when αč¡1. For the β index, the network forms tree pattern when β<1 and single circuit when β=1. β>1 indicates more complicated connectivity. γ index ranges from 0 to 1. γ=0 means no nodes were connected while γ=1 means every node is joined by another [17].

Our results showed the road network has heterogeneity at county scale . The indices differed greatly among 39 counties. The road α index varied from 0.21 to 0.83 and β index from 0.64 to 2.46.γ index from 0.12 to 0.50. Figure 2 showed the relationship between α, β, γ index and road density was positive and significant.

3.2.2 The network features trend of road combination with different road grade

The road network was comprised by roads of different grades. Also their combination has inherent regularity. In the study area, road type, combination, and road density exists spatial uneven distribution. To find the relationship between network features and the road combination, we calculated the coefficients of road density of different grades and further the α, β, γ index of road extension. The results showed that there existed linear relationship between different road classes (Table 1). It is evident that better correlation can be found between the lower grade roads and the adjunct grades. This may suggest that road configuration have a gradual evolution as a whole. Also the human disturbance

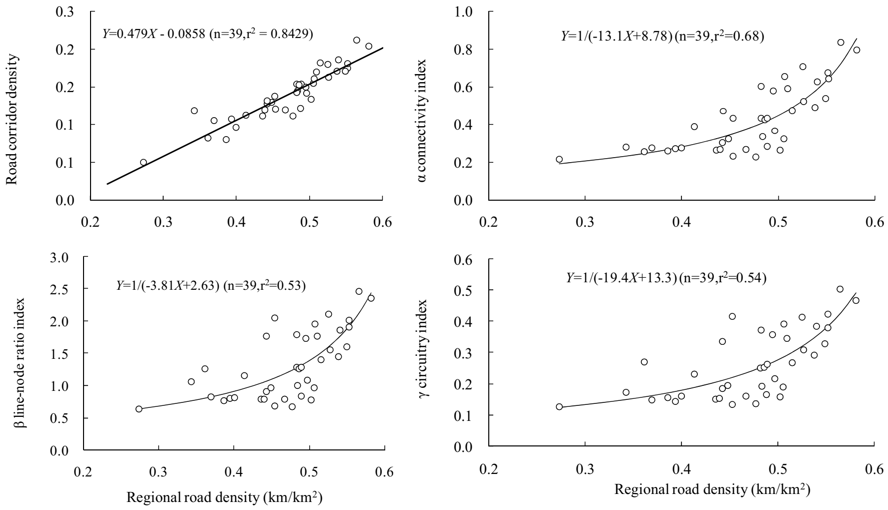

Figure 2: Relationship between average elevation and regional road length, density

penetrating into the wildness was followed by the road network extension.

Table 2: Relationship between regional road network and landscape characteristics

Road grade	Class I	Class II	Class III	Class IV	Class V
Class I	1				
Class II	0.473	1			
Class III	0.313*	0.305*	1		
Class IV	0.600**	0.365	0.324*	1	
Class V	0.716**	0.421	0.538**	0.722**	1

Figure 3 showed the network feature with different road combination in the whole Lancang river valley. The results showed that α, β, γ index all increased with the network expansion. The α index is close to 0 when only class I road exist. The values of β indexes indicated that more complicated connectivity exist in the road extension. The trend of γ index accorded with α and β index.

3.3 Relationship between road network features and landscape change in Lancang River Valley

Road network can be considered as disturbance corridor. It is assumed that road network complexity have certain relations with landscape change.

We analyzed the relationship between characteristics of regional landscape and road network features (Fig. 4). We used Shannon-Wiener index, average patch area, and patch density to describing the landscape pattern with Fragstat software (Fig. 4b). Also, landscape in 1980 and 2000 were compared.

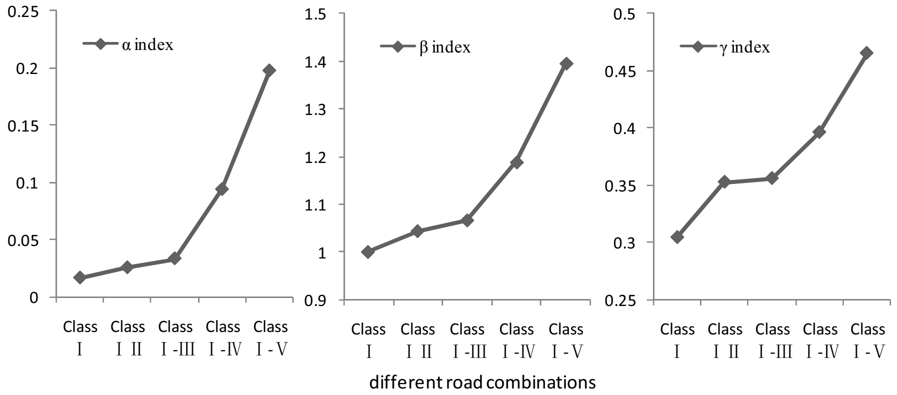

Figure 3: The trend of network features under different road combinations

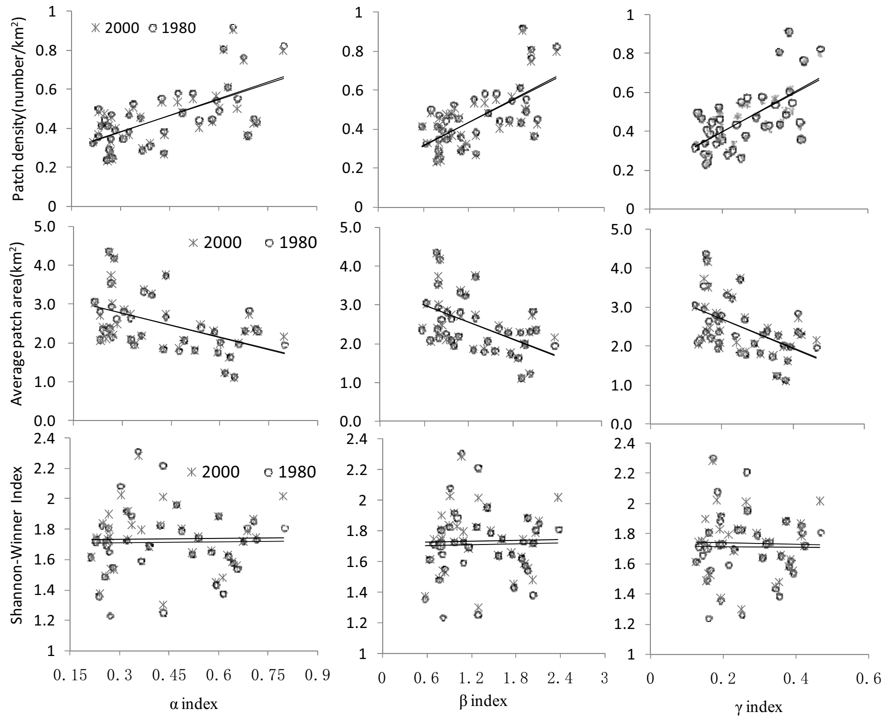

Figure 4: Relationship between regional road network features and landscape pattern

Figure 4 showed that landscape pattern have significant relationship with α, β, γ index. Spatially, regional ecological pattern changed greatly with the formation of road network. Using Pearson's correlation, we analyzed the relationship of 39 counties at county scale. The results showed that the splitting effect of road network caused the increase of patch density (patch number), while the decrease of average patch area. The results showed that the splitting effect induced the landscape fragmentation. But the Shannon-Wiener indexes were uncorrelated with road network features. That means the types of landscape varied little.

4 Discussions

Many researchers have focused on the effects of major roads while underestimated the minor roads' effect. So broad-scale studies of the impacts of roads should be considered. At the landscape level, both major and minor roads cause a reduction of interior habitat area and an increase in edge. The increase in landscape fragmentation by the additional minor roads has implications for biodiversity and ecosystem management, especially for species with limited migration or requirements of large areas of interior habitat [4].

Some studies showed that landscape indices showed greater fragmentation by roads in areas with higher housing density[18]. At a larger scale, our results proved that road hierarchy have a close relationship with the length of different road classes and also influence the vegetation pattern. Our results will be helpful for conservation and management of vegetation in Xishuangbanna with unique and typical tropical vegetation in Southwest China. The relationships between road classes, vegetation types and landscape fragmentation also provide insight into the complex relationships among social, institutional, and environmental factors that influence where roads occur on the landscape.

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