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A Landscape Pattern Analysis Method Based on Boundaries and Nodes: A Case Study in Upper Minjiang River, China

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Abstract: Traditionally, patch-based analysis at the landscape scale fragmentation has been used in the study of landscape ecology while the study of boundary and node has not been considered as much detail until recently. This study investigated the possibility of applying boundary- and node-based methods in landscape pattern analysis to the upper reaches of the Minjiang River in the southwestern China. Boundary-based and node-based landscape indices were selected to be used in analyzing changes in landscape patterns, and the results were compared with analysis using traditional pattern indices. We compared the responses of patch-area-based, boundary-length-based and node-number-based indices, and concluded that boundary-based and node-based indices are more sensitive to disturbance than patch-based indices with various patterns, and node-based indices are even more sensitive than boundary-based ones. Thus, the results suggest that boundary-based and node-based pattern analysis methods provide helpful supplementary information to traditional patch-based pattern analysis methods. The results about pattern dynamics of landscapes in the upper reaches of the Minjiang River based on boundaries and nodes showed that with human disturbance, the dominance of forest landscape was weakened by other landscape types; thus the landscape pattern of the study area became more homogeneous and the boundary network became more complex. These changes further augmented disturbance interfaces in the landscape and increased the possibilities of further landscape fragmentation.

Keywords: landscape; pattern index; patch; boundary; node; Minjiang River

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1 Introduction

The traditional pattern parameters used to describe a landscape were patch-based (Ruiz and Domon, 2009; Zhao *et al.*, 2010; Hassett *et al.*, 2012). As a component of landscape, landscape boundary can be classified into types with the use of length and number, and a boundary network that is composed by all the boundaries in a landscape has nodes, mesh size and network connectivity. Boundary network structure has impacts on landscape function in the same way as other aspects of a landscape such as patch configuration. Boundary dynamics often provide the most direct evidence of landscape change. Compared with patch-based studies, boundary-based studies provide new perspectives in understanding landscape processes (Wen *et al.*, 2008).

In recent years, landscape pattern analysis has been increasingly concerned with the use of boundary-based pattern analysis (Albeke *et al.*, 2010; Buyantuyev and Wu, 2010; Robles *et al.*, 2010; Sitzia *et al.*, 2010; Carroll *et al.*, 2012), but most traditional studies had considered boundary characteristics secondarily (Lovett-

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Doust *et al.*, 2003; Arroyo-Rodríguez and Mandujano, 2006; Bailey *et al.*, 2007). Studies those have considered boundaries had mostly focused on the structure and function of a single boundary type (Stamps *et al.*, 1987; Cadenasso and Pickett, 2000; 2001; Bartholomew *et al.*, 2008; Qureshi *et al.*, 2011; Polakowska *et al.*, 2012). Therefore, landscape pattern analysis based on patch boundaries still needs to be explored in considerable detail. Metzger and Muller (1996) studied landscape boundary complexity, defined a covert as the place where three or more land cover types converge (i.e., convergence points or coverts), and proposed two new metrics: covert percent and boundary diversity index. Land type percent area, boundary type percent length, fragmentation index, covert percent, boundary type number and boundary diversity indices were used to describe landscape boundary complexity, and the results showed that quantitative description of landscape boundary complexity is useful for landscape pattern analysis, while analysis of coverts can further improve the description. Zeng and Wu (2005) analyzed boundaries between landscape components to describe relative spatial locations of landscape components. In addition, several landscape metrics, such as the diversity, evenness and heterogeneity indices, were calculated based on length and number of boundaries. Because they are based on area of various patch types, the traditional diversity and heterogeneity indices can not measure landscape heterogeneity effectively when the area percentages of various patch types are the same (Xiao *et al.*, 2003). Since boundaries and nodes indicate places where the borders of different patches join each other and reflect the relative locations of these patches, metrics based on both boundaries and nodes are expected to be able to contain various types of information about landscape patterns in addition to the types of information available from patch-based metrics, and thus provide a useful complement to traditional metrics.

Figure 1a shows three patch types (A, B and C) in matrix M. When the landscape changes from the pattern of Fig. 1a to Fig. 1b, the percentages of areas covered by the various patch types do not change, and for patch type C and matrix M, boundary type and length percentages of various boundary types do not change either. However, the patterns have changed at both the landscape and patch type levels. Interfaces in the landscape have increased, types A and B have become more fragmented, and the number of nodes on boundary of type C has increased. The consequences of change in type C can not be ignored, because they may lead to many changes in ecological processes. For example, animals that used to move along the boundary between type A and B may disturb landscape C more frequently. Nodes have no length or area, but node type is an effective measure that can be used to describe adjacency relationships between the various patches. When the landscape changes from the pattern of Fig. 1c to Fig. 1d involving patch type or boundary type change, a new node type will appear. So we believe that the sensitivity of different metrics in describing pattern change follows this order, node-based metrics > boundary-based metrics > patch-based metrics.

During the past couple of years, node-based metrics played an irreplaceable role in studies on the spatial

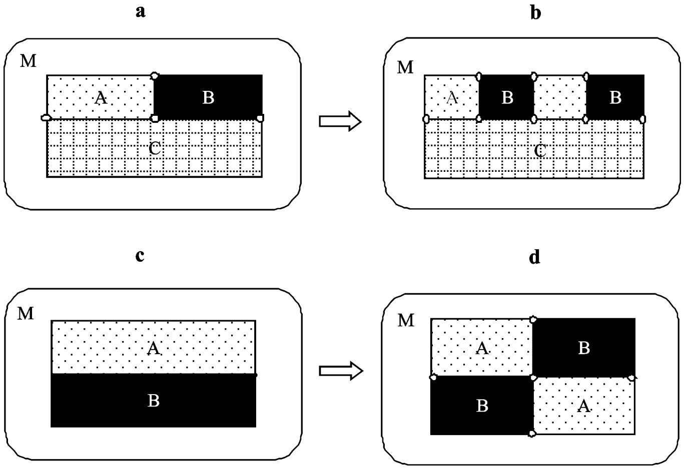

Fig. 1 Sketch map for sensitivity of patch, boundary and node to pattern change

structure of road networks (Kociolek *et al.*, 2010; Duan and Lu, 2013). The structure of the road network of Wuhan Metropolitan Area was analyzed from three aspects, which were importance of road intersections, accessibility of road intersections and clustering of road intersections (Liu *et al.*, 2012). Metrics based on nodes, such as node degree, node betweenness, accessibility and clustering coefficient, can be used to describe these aspects.

The objective of this study is to investigate the effectiveness of boundary-based and node-based metrics in describing changes of landscape patterns, with a case study in the upper reaches of the Minjiang River of the southwestern China. By comparing the sensitivities of boundary-based, node-based and patch-based metrics in reflecting landscape pattern changes, we intend to derive the value of boundary- and node-based metrics in pattern analysis.

2 Materials and Methods

2.1 Study area

Located on the transition zone from the Qinghai-Tibetan Plateau to the Sichuan Basin in the southwestern China, the upper reaches of the Minjiang River (30°45′–33°10′N, 102°00′–104°00′E) has plateau topography in the northwestern part of this region and a mountain-valley pattern in the southeastern part with elevation from 730 m to 5000 m above sea level, covering 23 000 km^2 of Sichuan Province (Fig. 2).

Plateaus occupy one third of the study area, with elevation ranging from 3000 m to 4500 m. The plateau area has a frigid and frigid-temperate climate, with annual precipitation of 730–850 mm and mean annual temperature of 5.7°C–13.5°C. The grassland dominated landscape is used for grazing. The elevation differences between the mountain and valleys in the southeast exceed 3000 m with significant elevation bioclimatic differentiation. Spruce and fir coniferous forest dominates between elevations of 3000–3800 m and provides the main forested water conservation area in the upper reaches of the Minjiang River. Frigid-temperate mixed and warm-temperate deciduous broadleaved forests occur at elevation below 3000 m. If these forests are harvested by humans, secondary shrubs often replace them. Subtropical evergreen broadleaved forest only occurs in southern part of study area at elevation below 1000 m. Natural vegetative cover is sparse in valleys because the floodplains along the Minjiang River and its tributaries are used for agriculture, and annual precipitation there is only about 500 mm. Both population density and reclamation rates are low.

2.2 Data and processing

Satellite images in 1974 (Landsat MSS), 1986, 1995, and 2000 (Landsat TM) were used to derive thematic

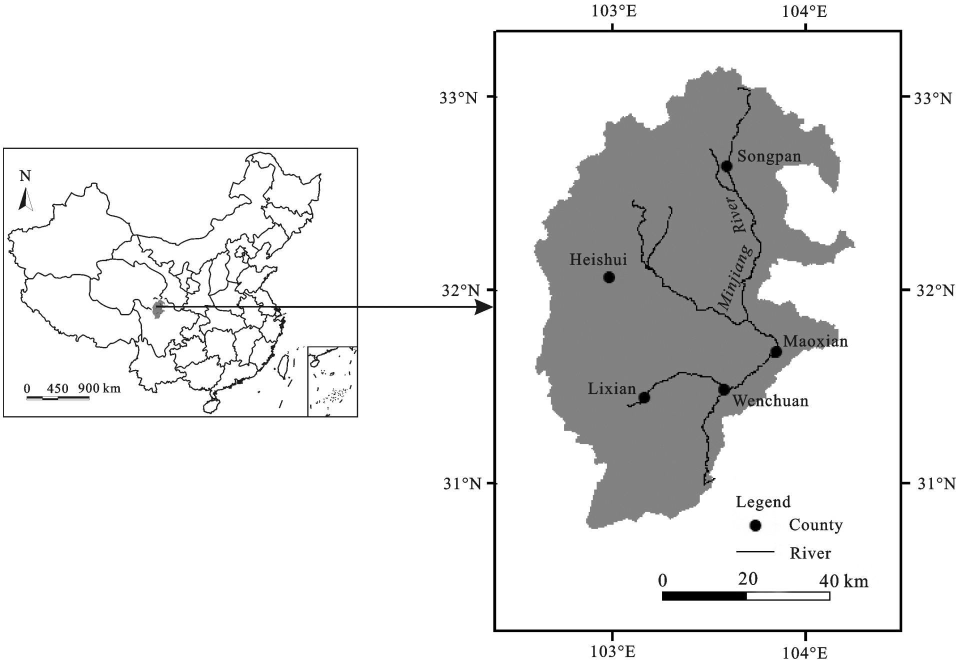

Fig. 2 Location of upper reaches of Minjiang River in China

landuse maps based on eight types: bare rock (including snow-covered and unused land), marsh, grassland, forest (including natural forests and plantations), shrub, water (including rivers, lakes and reservoirs), farmland (including cultivated land and orchards), and urbanized areas (including residential and industrial land). The images were geometrically corrected and geocoded to the Transverse Mercator coordinate system, using topographic maps of 1：10 000. Land use types were determined by a combination of supervised classification and manual interpretation of satellite images, supplemented with secondary information on climate and geomorphology, vegetation maps, and ground truth data (Kilic *et al.*, 2006). To determine the accuracy of the image classifications, the stratified random sampling method was used to generate 140 reference points for each of the classified images. One hundred forty reference points were located in the field with the help of a global positioning system (GPS) with ±5 m error for ground-truthing. The kappa accuracy index (Congalton, 1991) was 85.2% in 1974, 87.5% in 1986, 90.3% in 1995, and 92.2% in 2000. Maps indicating the location of boundaries and nodes, and elevation distribution of boundaries were obtained by ArcGIS 9.0. Maps indicating the location of boundaries and nodes, and elevation distribution of boundaries were obtained from landuse maps and DEM .We used both ERDAS Imagine 9.0 and ArcGIS 9.0 to process data.

2.3 Methods

Several landscape types in the upper reaches of the Minjiang River, including forest, shrub land, grassland and other natural vegetation, play crucial roles in soil and water conservation. Agricultural activity is one of the most important types of disturbance. Especially in the 1980s, deforestation is another type of disturbance that provides important resources for local economic development. In this paper, the boundary dynamics between agricultural landscape and natural landscape are used to reflect the human impact on natural vegetation. Unlike traditional studies, this paper uses metrics based on boundaries and nodes to measure landscape pattern change. Since the elevation difference between the mountain and valleys is quite high, while the change of boundary elevation is often the reflection of the driving factors of landscape change, we take the boundary elevation as the index to describe the landscape changes of the upper reaches of the Minjiang River.

Boundary length, number of boundaries, boundary elevation, number of nodes and other indicators were selected to describe the pattern of boundary network across the landscape. Pattern indices based on patch area, boundary length and node numbers were chosen for comparison. The diversity, evenness, heterogeneity and complexity indices at both the landscape and class scales were calculated as follows (Zeng and Wu, 2005):

$$H(b) = \sum_{i=1}^{n} p_i \ln p_i \tag{1}$$

$$E(b) = H(b) / \ln(n) \tag{2}$$

$$H(l) = H(b) / \ln(N) \tag{3}$$

$$C(s) = H(b)^2 / \ln(N) \tag{4}$$

where $H(b)$, $E(b)$, $H(l)$ and $C(s)$ are diversity, evenness, heterogeneity and spatial complexity, respectively. In pattern analysis based on patches, P_i stands for the percent of an area occupied by patch type i in the landscape; n is the total number of landscape patch types; and N is the total number of landscape patches. In pattern analysis based on boundaries, P_i is the percent of boundary type i calculated from the length of all boundaries; n is the total number of landscape boundary types; and N is the total number of the boundaries across the landscape. In pattern analysis based on nodes, P_i is the percent of node type i calculated from the total number of nodes in the landscape; n is the number of node types in the landscape; and N is the total number of the nodes across the landscape.

Although the above pattern indices based on patch area only apply to the landscape scale, each patch type has a variety of boundary and node types. Therefore boundary-length- and node-quantity-based indices can be used to describe the characteristics of different patch types. The above four indices at the class scale are:

$$H_i(b) = \sum_{k=1}^{n} p_k \ln p_k \tag{5}$$

$$E_i(b) = H(b) / \ln(n) \tag{6}$$

$$H_i(l) = H(b) / \ln(N) \tag{7}$$

$$C_i(s) = H(b)^2 / \ln(N) \tag{8}$$

where $H_i(b)$, $E_i(b)$, $H_i(l)$ and $C_i(s)$ are diversity, evenness, heterogeneity and spatial complexity of patch type i, boundary type i or node type i, respectively. In pattern analysis based on boundary characteristics; P_k is the percent length of boundary type k calculated from the total circumference of patch type i; n is the number of boundary types related to patch type i; and N is the number of boundaries related to patch type i. In pattern analysis based on node characteristics, P_k is the percent of node type k calculated from the total number of nodes related to patch type i; n is the number of node types related to patch type i; and N is the total number of nodes related to patch type i.

The diversity index quantifies the level of diversity seen in the landscape elements, which increases as the number of types. When there is only one class in the landscape, the diversity index is 0. Also, the diversity index increases with a decrease in relative area (length or number) of various types of scenarios. The evenness index is used to describe the relative weight of different element types and ranges between 0 and 1. A low value for evenness indicates a greater relative area (length or number) for each unique class, and a higher level of dominance level. As the relative area (length or number) of each class become more uniform, the value for the evenness index approaches to 1. The heterogeneity index $H(l)$ can be used to express the possibility of a landscape that could be divided into different significant classes. When the landscape patches (boundaries or nodes) have a maximum number of types, namely $n = N$, $H(l)$ reaches to the maximum value 1. Since the landscape heterogeneity index may have the same value at different levels of complexity (e.g., the number of different types), we chose the spatial complexity index $C(s)$ to measure the binding characteristics of spatially adjacent patches and to reflect the degree of fragmentation of a given mosaic structure (Zeng and Kong, 2002). Herein a boundary refers to the edge where two types of patches adjoin. Multiple boundary types may occur on the perimeter of a patch. A node refers to the junction where three or more patches adjoin. Boundary-length-based and node-number-based indices were calculated by ArcGIS analysis function module on the attribute table, and patch-area-based indices were calculated by using Fragstats software.

3 Results and Analyses

Based on the eight landscape types mentioned above for the upper reaches of the Minjiang River, 23 boundary types and 41 node types were derived. Boundary types were dominated by those between forest, shrub, grassland, water and farmland. The length of boundaries for these five dominant boundary types accounted for over 90% of the total length of all boundary types.

3.1 Comparative analyses between boundary, node and patch-based indices

3.1.1 Analyses at landscape scale

The diversity, evenness, heterogeneity and spatial complexity based on patches continued to increase from 1974 to 2000 (Fig. 3). Since the number of patch types did not change, the increase of diversity and evenness reflected that the relative area among different patch types in the landscape became closer to each other and the dominant types such as forest decreased in the landscape. Specifically, this change was caused by the decrease in forested area and the increase in other landscape types.

Agriculture is the main human activity in the upper Minjiang River region. Its development is the main driving force for landscape change. The spatial extent of farmland decreased after three years of natural disasters during 1959–1961. Around 1980, the household contract responsibility system stimulated farmers′ enthusiasm for production, which resulted in a significant increase in the spatial extent of farmland (Zhao *et al*., 2006). With the population increase since 1980, the farmland area increased continuously. Deforestation resulted in an increase in landscape boundary length, weakened the previous dominance of forested landscapes, narrowed the gaps among lengths of different boundary types, and increased landscape diversity and evenness. The landscape heterogeneity and spatial complexity indices had similar trends to the landscape diversity index (Fig. 3).

Trends of changes were basically the same for boundary-length- and node-quantity-based indices. From 1974 to 1995, all the values for landscape diversity, evenness, heterogeneity and complexity based on boundary length and number of nodes increased. From 1995 to 2000, the boundary- and node-based indices decreased, reflecting different information from patch-based pattern analysis. From 1974 to 2000, comparison between boundary-based and node-based indices showed that the changes of node-based index were more obvious than those boundary-based one except for the landscape evenness index. Therefore, node-based indices might be more sensitive to landscape pattern changes.

As boundary and node both vary little with time (Table 1), the diversity indices based on boundaries or nodes reflect length proportion changes of various boundary types or number proportion changes of various node types. The boundary-based and node-based diversity indices decreased after 1995, which indicated the increase of difference in the proportion of length for different boundary types and difference in the proportion of different type nodes.

Forest boundary is the dominant boundary type in the study area, while farm boundaries were the lowest in number. Since the implementation of a policy designed to reforest cultivated land in 1998, scattered farmland patches on steep slopes have been reforested. Since the farmland patch size in the upper Minjiang River was very small (< 100 ha), reforestation caused entire farm patches to disappear and farmland boundaries apparently declined during 1995–2000. This is probably the most important factor affecting boundary pattern and node pattern characteristics.

3.1.2 Analyses at class scale

For the same landscape type, there is only one type of patch. Therefore the comparison at the class level omitted patch-based metrics and was carried out between boundary- and node-based landscape pattern indices. Forest, shrub, grassland, and farmland were analyzed in this paper. At the landscape scale pattern analysis, node-based pattern indices were more sensitive than boundary-based indices. We will compare the sensitivities of indices further based on these two features.

Unlike patch-based pattern indices, boundary- and node-based pattern indices reflect variations of patches' relative position, such as the heterogeneity and complexity of a particular landscape type's relative spatial relationship with other surrounding landscape types. Boundary-based indices reflect neighboring relationships between two landscape types and node-based indices reflect neighboring relations among three or more landscape types.

Boundary-length-based diversity, evenness, heterogeneity and complexity indices showed decreasing trends for forest from 1974 to 2000 (Fig. 4a). The node-based evenness index also showed a decreasing trend, while the three other node-based indices showed slightly different variations: decreasing from 1974 to 1986, increasing from 1986 to 1995, and decreasing again from 1995 to 2000 (Fig. 4a). Boundary-based indices indicated that the heterogeneity of landscape types adjacent to forest had decreased. The harvest of low elevation forest had caused the decrease of low elevation forest boundaries, for example, forest and water boundary, while boundaries between shrub and forest increased. Thus boundaries between shrub and forest

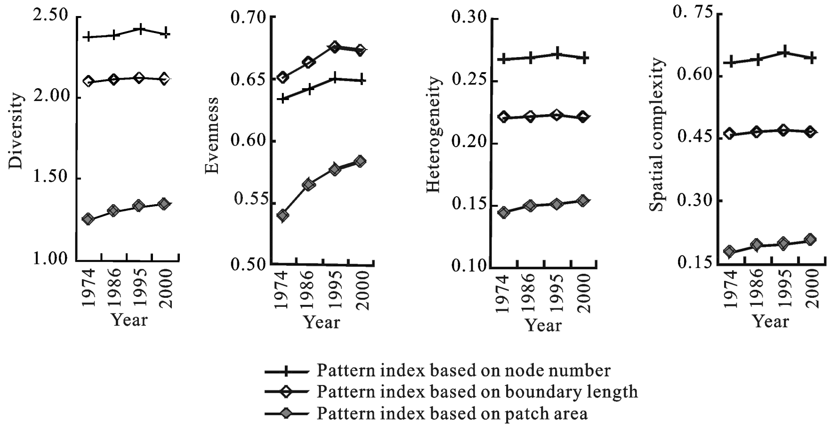

Fig. 3 Pattern analysis at landscape scale based on number of nodes, boundary length, and patch area

Table 1 Changes of node and boundary in landscape from 1974 to 2000

Period	Change of node types	Increase rate of node number (%)	Change of boundary type	Increase rate of boundary number (%)	Increase rate of boundary length (%)
1974–1986	+2; –3	1.42	0	1.9	6.3
1986–1995	+1; –1	0.92	0	0.8	2.8
1995–2000	–1	4.75	0	3.9	1.8

Notes: '+' represents increasing in the types; '–' represents decreasing in the types and 0 represents no change in the types became increasingly dominant among forest boundaries, which in turn decreased landscape evenness. Node-based landscape indices showed that landscape types surrounding forest did not change obviously over time.

Indices of shrub landscape exhibited opposite variation trends to those of forest landscapes. Boundary-based landscape indices maintained a steady increasing trend from 1974 to 2000, whereas node-based landscape indices showed more significant variation. Node-based indices exhibited steady increases from 1974 to 1995. In particular, a more significant increase occurred from 1974 to 1986, but decreased after 1995 (Fig. 4b). One can conclude that the diversity of landscape types adjacent to shrub patches increased. The changes included an increase of farmland and secondary shrub expansion caused by human deforestation, which resulted in increases in farmland and shrub boundaries. The natural forest protection project demanded that small-sized, scattered farmland patches should be restored to forest. However, because of local economic development, deforestation in the study area is not completely prohibited. Secondary growth shrub area increased continuously

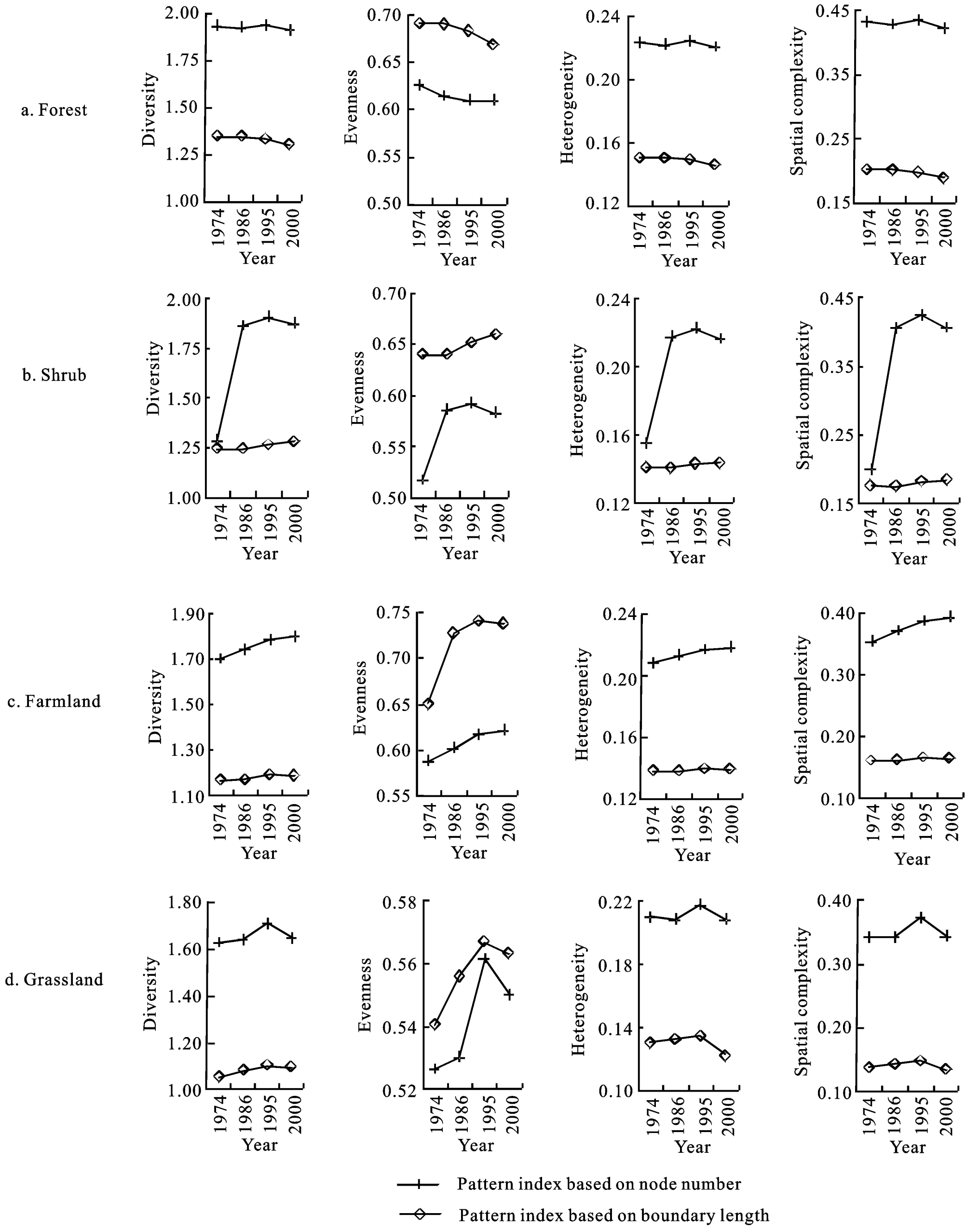

Fig. 4 Pattern analysis at class scale based on number of nodes and boundary length for forest (a), shrub (b), farmland (c), grassland (d)

after 1995, together with some formerly created land patterns formed by adjacent farmland and shrub, resulting in large patches of farmland expanding along with secondary shrub, and shrub landscape indices varying in complicated ways after 1995.

For farmland landscapes, boundary- and node-based diversity and heterogeneity indices both exhibited increasing trends (Fig. 4c). This could be caused by an increase in the spatial extent of farmland. After 1995, reforestation resulted in the disappearance of some farmland patches, which in turn lead to a decreasing trend in boundary-based evenness of farmland landscapes. The node-based evenness index, on the contrary, only showed small increasing trends. It can be concluded that node-based indices are less sensitive to the changes in farmland evenness than boundary-based indices, perhaps because the disappearance of farmland patches were mostly island patches and their disappearance had less influence on the number of nodes than that on boundaries.

For grassland, node-based and boundary-based indices both increase from 1974 to 1995 (except heterogeneity) and then decreasing (Fig. 4d). The difference is that the increase of node-based indices is not obvious from 1974 to 1986. Grassland and shrub landscapes have basically the same pattern of variation. However, the pattern of variation for shrub was more obvious from 1974 to 1986, whereas the pattern of variation for grassland was more obvious after 1995. Shrub at low elevation suffered from intensive human disturbance in the 1980s, while grasslands at high elevation area were threatened by agricultural development in the late 1990s.

3.2 Pattern dynamics of landscapes

From 1974 to 2000, total boundary length, number of boundaries and number of nodes showed trends of continuous growth. However, the rates of increase in boundary length changed with time. Total boundary length had shown significant growth from 1974 to 1986 and a minor increase from 1986 to 2000. According to the increase rate of boundary number and node number, the number of boundaries and nodes had shown significant growth from 1995 to 2000, compared to that from 1974 to 1995 (Table 1).

Mean boundary length increased from 1974 to 1995 and then decreased after 1995 (Fig. 5). Mean boundary length is related to total boundary length and number of boundaries. The increase in mean boundary length before 1995 was caused by the increase in total boundary length rather than by the number of boundaries. The decrease of mean boundary length and increase of number of boundaries after 1995 indicated that the number of shorter boundaries increased and landscape fragmentation intensified during that period. Initially, from 1974 to 1995 the average elevation of boundaries decreased but it increased slightly from 1995 to 2000. From 1974 to 1995, total boundary length increased significantly and their average elevation decreased, which meant that new boundaries appeared at lower elevation. Human activity is a major factor influencing boundary pattern change. The increase in the mean elevation of boundaries from 1995–2000 was probably caused by a decrease in human disturbance in low elevation areas, as a result of the natural forest protection policy implemented since 1998.

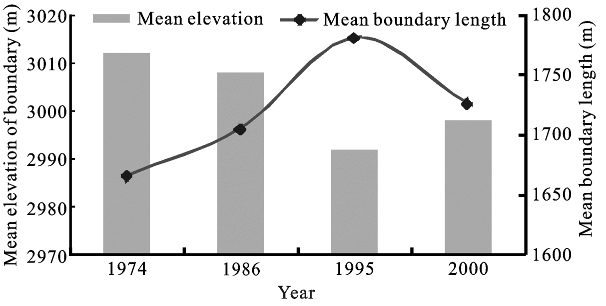

Fig. 5 Change in mean elevation and mean boundary length in study area from 1974 to 2000

4 Discussion

The results from Zeng and Kong (2002) showed that landscape diversity and evenness indices based on patches and boundaries had basically similar change trends, but the indices based on boundaries can reflect change of boundaries in landscape better than patch-based indices, and can be used to analyze landscape spatial complexity; this would be difficult to accomplish with traditional landscape pattern indices. The results of this paper confirmed their conclusion. We also found that node-based indices were more sensitive and can even reflect more pattern information than boundary-based and patch-based ones. Thus, node-based and boundary-based pattern analysis is very valuable as a supplement to traditional pattern analysis.

The harvest of low elevation forest had caused that boundaries between shrub and forest became increasingly dominant among forest boundaries, which in turn decreased landscape evenness. Grassland and shrub landscapes had basically the same pattern of variation. However, the pattern of variation for shrub land was more obvious from 1974 to 1986, whereas the pattern of variation for grassland was more obvious after 1995. Shrub land at low elevation suffered from intensive human disturbance in the 1980s, while grasslands at high elevations area were threatened later. In this paper, we took the mean elevation of boundaries as an index describing landscape pattern change due to the complex topography and the mountain-valley pattern in study area. However, the index would be actually needless when the study area is plain or city.

This study also found that among the four selected pattern indices, the complexity and landscape heterogeneity indices had almost the same trends in variations at both the landscape and class levels. There could be high information redundancy between them. Objective of this study is to derive the value of boundary- and node-based metrics in pattern analysis through comparing node-based, boundary-based and patch-based indices. Apparently, some indices are simple, however, have many practical implications, such as the number of node (boundary) type, the number of node (boundary) and boundary length.

5 Conclusions

This paper analyzed landscape pattern by using boundary-based and node-based indices, and compared the efficiencies of boundary-based, node-based indices with traditional patch-based index in reflecting landscape pattern changes. Comparative analysis showed that pattern indices based on patches, boundaries and nodes had similar trends in reflecting pattern change at the landscape scale, while the indices based on boundaries and nodes were more sensitive to pattern changes than those based on patches. At the landscape and class scale, node-based index was more sensitive to landscape pattern changes than boundary-based indices except for the evenness index and can reflect more pattern information than the latter.

Human disturbance has caused the landscape boundary network structure of the upper reaches of the Minjiang River to become more complicated. Boundary length, number of boundaries and number of nodes increased significantly, and number of boundaries and nodes increased faster than boundary length after 1995, which further resulted from the fragmentation of landscape. Forest landscape patterns became simplified and the dominance of forested habitat was weakened. As a result of the pattern changes at the class scale, the landscape patterns in the upper reaches of the Minjiang River became more complicated and the percentages of different landscape types became more uniform, which is shown in the landscape indices. Human disturbance made the landscape more fragmented and the boundary network more complicated, which increased the disturbance interface in the landscape. Without appropriate measures for ecological protection, landscape-scale fragmentation is expected to accelerate.

Although both boundary- and node-based indices are more sensitive than patch-based indices, patch-area-based pattern analysis should not be replaced. It is proposed that different pattern indices should be combined together to better describe landscape patterns. The introduction of boundary network and node pattern provides a new way of thinking for landscape pattern analysis. Further studies on pattern indices specially designed for boundaries and nodes are still needed.

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