ACTA ECOLOGICA SINICA
Volume 28, Issue 11, November 2008
Online English edition of the Chinese language journal

Available online at www.sciencedirect.com
ScienceDirect

Cite this article as: Acta Ecologica Sinica, 2008, 28(11), 5521−5531.

RESEARCH PAPER

Pattern analysis in landscape ecology: progress, challenges and outlook

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Abstract: Landscape pattern indices or landscape metrics, an important means in landscape pattern analysis, has resulted in the prosperity of landscape ecology. However, landscape pattern analysis was criticized recently for its poor correlation with ecological processes. In this paper, the current situation and challenges in landscape pattern analysis was elaborated, and the future of landscape pattern analysis was discussed. We believe that the landscape metrics is still the main method in spatial pattern analysis, and is important for landscape ecology. However, there are 3 challenges in landscape pattern analysis: (1) how to develop new methods by integrating explicit ecological sense in landscape pattern analysis? (2) How to link landscape pattern and ecological processes? (3) How to apply the theory of "matrix-patch-corridor" to practice? In future, 5 issues are to be addressed: (1) to develop a methodology to describe landscape pattern in a dynamic manner; (2) to explore the ecological sense of landscape pattern using a series of landscape metrics; (3) to develop new methods for landscape pattern analysis related to ecological processes; (4) to conduct landscape pattern analysis at multi-dimensions; (5) to explain the relationship between landscape pattern and ecological processes by multi-scale pattern analysis.

Key Words: landscape metrics; landscape pattern analysis; challenge; perspectives

Landscape pattern is the arrangement of landscape components with different sizes and shapes[1]. Composition and configuration of landscape components are basic properties of landscape pattern[2]. Composition describes the number and relative frequency of components, and configuration refers to the spatial arrangement of the landscape components[2]. Spatial heterogeneity means the complexity and variability of landscape pattern in both spatial and temporal dimensions[3], essentially the spatiotemporal change of landscape components in composition and configuration. Sometimes, landscape pattern and landscape heterogeneity can be used as substitute for each other[3]. Landscape pattern analysis studies the composition of landscape components and their spatial arrangements[4], and depicts them using certain methods, such as characters, graphs and landscape indices. The aim of spatial analysis is to discover meaningful regularity from landscape mosaics which seems to be out-of-order, and to determine factors and pertinent mechanisms controlling landscape patterns[4–6].

Landscape ecology deals with landscape pattern, functioning and dynamics[7,8]. In order to explore the interaction between landscape pattern and ecological processes[9], and to detect landscape dynamics and functioning[10], it is essential to quantify landscape pattern first. Also, landscape pattern analysis plays an important role in resource management as well as biodiversity conservation[3]. All these have made spatial pattern analysis a vital part in landscape ecological research in America and all over the world[11]. However, for years, spatial pattern analysis stays at the depiction of landscape pattern characteristics, and is unable to indicate the processes related to the pattern, thus causing great controversies. Even though, we believe that the spatial pattern analysis is still an important part of landscape ecological research, and will play a key role in the development of landscape ecology.

Received date: November 19, 2007; Accepted date: August 29, 2008
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1 Present status of landscape pattern analysis

At present, there are 2 kinds of landscape pattern analysis: normal analysis and analysis related to certain ecological process. Normal analysis usually uses landscape indices to describe landscape composition and configuration in a certain study area. It is the preliminary form of landscape pattern analysis, from which most of the landscape indices arise. As landscape ecology develops, and as the interaction between pattern and process attracts more and more attention, high level landscape pattern, pattern analysis related to certain ecological process, comes up. It will play a leading role in landscape pattern analysis at present and in the future.

1.1 Landscape pattern analysis: landscape indices

Various methods for landscape pattern analysis exist in landscape ecology[12], such as words, graphs and landscape indices[4,13,14], among which landscape indices are used most widely[15–19]. Quantifying landscape pattern is the first step in exploring causes and ecological meanings of landscape heterogeneity[11]. Landscape indices can simply reflect composition and configuration of landscape patterns[20], and thus are qualified for fulfilling this requirement. Furthermore, comparison of landscape patterns with either different times or different locations can be realized by using landscape indices[19].

1.1.1 Types of landscape indices

According to different objects described, landscape indices can be categorized into two groups: indices describing landscape components and indices describing whole landscape features. Indices describing landscape components can be divided into 4 categories, including area index, shape index, connectivity index and configuration index, according to different functions. Those four kinds of indices, plus diversity index, comprise the indices describing the whole landscape features. Due to the rapid development of GIS and computer techniques, some new landscape indices emerge[21,22], such as lacunarity index[23], aggregation index[24] and location-weighted landscape contrast index (LCI)[25].

Table 1 represents landscape indices mainly used in 100 journal papers published in 1979–2008. It can be found that area index, shape index, biodiversity index, configuration index and fragmentation index are used frequently (Fig. 1). Except area index (28.97%), which is used more frequently, and fragmentation index (13.96%), which is less frequently used, the frequencies of the other three kinds of indices are very close to each other. In course of statistic analysis, we

Table 1 Statistic analysis of the landscape indices used in the referenced Chinese literature

Type	Index	Times	Frequency (%)	Type	Index	Times	Frequency (%)
Area index	PA	29	5.06	Diversity index	SHDI	34	5.93
	NP	40	6.98		SIDI	5	0.87
	PD	40	6.98		Hi	37	6.46
	MPS	40	6.98		SHEI	17	2.97
	LPI	17	2.97		Ev	18	3.14
	Total	166	28.97		Total	111	19.37
Shape index	AWMSI	8	1.40	Spatial configuration index	PCI	5	0.87
	MSI	15	2.62		DI	32	5.58
	AWMPFD	13	2.27		CO	6	1.05
	MPFD	19	3.32		CI	10	1.75
	FDI	29	5.06		Is	21	3.66
	LSI	20	3.49		CONTAG	17	2.97
	PAFRAC	6	1.05		AI	15	2.62
	Total	110	19.20		Total	106	18.50
Fragmentation index	ED	23	4.01				
	FN	34	5.93				
	SL	5	0.87				
	PLAND	18	3.14				
	Total	80	13.96				

PA, patch area; NP, number of patches; PD, patch density; MPS, mean patch size; LPI, maximum patch index; AWMSI, area-weighted patch shape index; MSI, mean shape index; AWMPFD, area-weighted mean patch fractal dimension; MPFD, mean patch fractal dimension; FDI, fractal dimension index; LSI, landscape shape index; PAFRAC, perimeter-area fractal dimension; SHDI, Shannon diversity; SIDI, Simpson diversity index; Hi, landscape diversity; SHEI, Shannon evenness; Ev, evenness index; PCI, patch cohesion index; DI, diversity; CO, cohesion index; CI, complexity index; Is, landscape isolation; CONTAG, contagion; AI, aggregation index; ED, edge density; FN, landscape fragmentation; SL, inner habitat area index; PLAND, percentage of landscape types

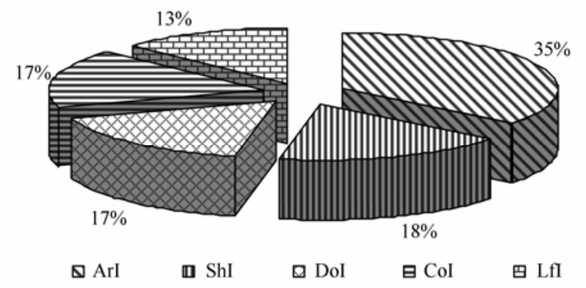

Fig. 1 Percentage of landscape indices used in referenced Chinese papers

ArI, area index; Shi, shape index; DoI, diversity index; CoI, spatial configuration index; LfI, landscape fragmentation index

found that the nomination of landscape indices is somewhat confusing, and there are up to 100 landscape indices used in Chinese literatures.

1.1.2 Duplication of landscape indices

In landscape ecology, many landscape indices with different formations represent the same meaning, such as diversity indices and evenness indices; mean patch density, mean shape index and fractal dimension index. Many studies indicate that it is needed to filter the indices before the performance of landscape pattern analysis because of correlation properties between landscape indices.

Using a multivariate factor analysis, Riitters *et al*.[26] calculated 55 landscape indices using 85 maps, and suggested a set of landscape indices as composite measures of landscape pattern, including average perimeter-area ratio, contagion, standardized patch shape, patch perimeter-area scaling, number of attribute classes and large-patch density-area scaling. By means of eliminating correlations through factor analysis and classification-tree method, Lausch and Herzog[27] filtered indices depicting the whole landscape features of two areas in Germany. Because of different data sources and data processing methods, the final sets of landscape indices for the two areas differed greatly. Thus, it is essential to establish a standardized process for the calculation of landscape indices using remote sensing imagery[28]. To avoid redundant information, filtering landscape indices by statistical methods is necessary in landscape pattern analysis[22,27]. However, Li and Wu[15] pointed out that landscape index sets, obtained by statistical methods, have no inherent ecological meanings until the interactions between landscape pattern and ecological processes have been reflected thoroughly and the sensitivity of landscape indices to scales has been addressed.

1.1.3 Landscape indices and ecological sense

Landscape patterns interact intensively with ecological processes[3], and landscape ecology mainly deals with such interactions[29]. The ultimate aim of landscape pattern analysis is to thoroughly portray the interactions[15]. If landscape indices are ecologically relevant and reflect important attributes of spatial pattern, they can functionally link the dynamics of ecological processes to spatial pattern[15,30]. Unfortunately, lots of spatial pattern analyses fail to reflect ecological processes due to landscape indices with large numbers but few classes and confusing ecological meanings.

Tischendorf[9] investigated the consistency of correlations between a set of landscape indices and 3 response variables (cell immigration, dispersal success and search time) from a simulated dispersal process across heterogeneous landscapes against variation in 3 experimental treatments: habitat amount, habitat fragmentation and dispersal behavior. It was found that a single landscape index cannot thoroughly reflect ecological processes; correlations between landscape indices and ecological processes depend on variables describing ecological processes; comparisons between different researches can be realized using the same variable to depict the same kind of ecological processes. Recently, ecologists seek to portray landscape pattern related to a certain ecological process using a single index, such as connectivity index presented by Verboom *et al*[31]. Taking non-point source pollution as an ecological process, Chen *et al*.[25] proposed a new landscape index, the location-weighted landscape contrast index, to evaluate the effect of landscape pattern on ecological process. The index has been proved to be practical in reflecting soil loss and non-point source pollution[32].

1.1.4 Landscape indices and scale effect

Landscape pattern and ecological processes as well as their interactions depend greatly on scale. Scale roots in the hierarchy and complexity of the earth, and it is inherent in natural world and sensed by human beings[33]. Therefore, scale can be categorized as intrinsic scale and observation scale. Observation scale is the measurement of spatial pattern and processes being studied, and it largely depends on human beings' capability of sensing. Intrinsic scale is the inherent organization of the earth and is out of the control of human beings. Only when the observation scale is in accord with intrinsic scale can depiction of landscape pattern and ecological processes be addressed exactly [34–36]. The sensitivity of landscape indices to scales is due to the difference between observation scale and intrinsic scale. Hence, it is essential to make observation scale precisely close to intrinsic scale. Development of remote sensing and GIS provides useful techniques to landscape ecologists[11,27]. With help of these techniques, many studies on scales have been carried out and several methods for scale detection, such as auto-correlation, semi-variance, lacunarity, scale variance and wavelet, have been proposed.

Though some progress in scale analysis has been achieved, many studies focus on spatial scales and ignore the temporal ones. Similarly, most landscape indices ignore temporal heterogeneity[3]. In fact, spatial pattern with various levels in the landscape hierarchy has not only different spatial scales, but also varied temporal scales. Temporal and spatial scales together represent characteristics of landscape pattern, and landscape pattern analysis should focus on both of them.

1.2 Characteristics of landscape pattern analysis

With the development of landscape pattern, two characteristics appear.

1.2.1 Analysis from one dimension to multi-dimensions

Only temporal or spatial characteristics cannot represent the whole features of a landscape pattern, so landscape pattern analysis has turned from one dimensional analysis (only spatial or temporal analysis) to multi-dimensional analysis, with consideration of both temporal and spatial scales.

The multi-dimensional pattern analysis is usually conducted together with driving factor analysis to detect causes for landscape pattern changes. With several landscape indices, Wang *et al*.[37] analyzed landscape pattern change during 1990–2000 in Dulan County, Qinghai Province, China. Results showed that landscapes with high economic benefits, such as croplands, dense woodlands, high-coverage grasslands, pools and constructive lands, increased during the study period. Mostly, these landscapes are man-made and driven by socio-economic development, and proper climate conditions strengthened their changes. However, landscapes, such as shrub lands, sparse woodlands and medium/low-coverage grasslands, decreased during 1990–2000. Most of them are natural landscapes, and mainly driven by climate conditions. Lots of similar studies exist. For example, Liu *et al*.[38], Ward *et al*.[39], Xu *et al*.[40], and Başkent and Kadioğullari[41], explored spatiotemporal changes of different landscapes as well as their driving factors.

Multi-dimensional analysis on landscape pattern mentioned above can effectively reveal spatial patterns and ecological processes as well as their interactions. However, driving factors are only represented by qualitative depictions, and sometimes not so convincing. Thus, quantifying driving factors and linking the factors to landscape patterns quantitatively should be enhanced in future studies. Upon this, we can optimize landscape patterns by modifying the controllable driving factors, or forecasting landscape changes affected by certain factors.

1.2.2 Key transect analysis based on general landscape features

Effects of ecological processes on landscape patterns can be reflected more exactly by one or more transects, such as a river or a road. Thus, studies on transects can exactly indicate the whole features of landscapes. Furthermore, the studies are easier to be conducted and the results are easier to be interpreted. Such studies often appear in ecological research on urban landscape, which depict the influence of urbanization on landscapes through analyzing spatiotemporal changes of key transects in a metropolitan area.

Gradient paradigm was first introduced into urban ecological research by McDonnell and Pickett[42]. Gradient means variation in the degree of urbanization, in terms of land-use intensity and human intervention[43]. Luck and Wu[44] first integrated the gradient paradigm and landscape indices to study the characteristics of landscape pattern along an urban- rural transect in the Phoenix metropolitan region, Arizona, USA. Recently, studies employing such method to analyze urban landscapes increase gradually, and tend to be integrated with multi-dimensional analysis[43,45–47]. Moreover, landscape gradient analysis is not confined to urban landscapes, and it is pretty useful for analysis of landscapes distributed along linear elements. Bi *et al*.[48] studied the gradient variations of landscape pattern along the Jinghe River and their driving factors. Bu *et al*.[49] evaluated the rationality of city railway planning in Dongguan City, China, based on the analysis of land use density and structures along the railway lines. However, in practice, it is essential to make sure whether the transects being studied fully reflect the whole landscape features.

2 Challenges in landscape pattern analysis

2.1 How to develop new methods for landscape pattern analysis by integrating ecological meaning?

Landscape indices played a vital role in the initial stage of landscape ecology research in 1980s. Using the indices, people can characterize the complicated world with several simple numerical values, which can greatly enhance peoples' understanding of landscapes. Meanwhile, landscape indices and software for landscape pattern analysis have largely promoted the development of landscape ecology. It is shown that the main feature of landscape ecology is the advent of landscape indices as well as software for spatial pattern analysis. However, as time passes by, ecologists are not satisfied with the mere depiction of landscape pattern. They turn their attentions to interactions between spatial pattern and ecological processes, and seek to characterize the interactions with landscape indices. Unfortunately, most landscape indices come from statistics[21] and geometry, and have no ecological meanings at all in their formulation[15,22]. All that the indices represent are present status and the whole feature of landscapes, which cannot reflect the interactions of pattern and processes, and fail to fulfill the high level of spatial pattern analysis. Therefore, to establish meaningful landscape indices or discover ecological meanings of existing indices has become principal tasks of landscape ecologists.

2.2 How to establish sound relationships between landscape pattern and ecological processes?

Several different processes may exist in one study area[15], such as soil and water loss, and species migration. Different processes interact with different landscape elements. Therefore, in order to detect interactions between different patterns and processes, it is necessary to develop ecologically meaningful landscape indices related to certain processes. For example, to determine landscape characteristics related to soil and water loss, we need indices that can reflect land use types, their configurations, elevations and slopes; for landscape analysis related to species migration, indices representing food distribution, habitat areas and their connectivity are needed. However, this can hardly be realized because most contemporary landscape indices are ecologically meaningless.

On the other hand, because most landscape indices originate in statistics or mathematics, they can only reflect the quantitative changes of landscapes rather than the qualitative ones. If the composition of a landscape remains unchanged but the spatial arrangement changes, patch area index and diversity indices will not change, whereas the effects of landscape pattern on ecological processes will probably change greatly. Take non-point source pollution in agricultural landscapes as an example. Croplands and forests are usually considered as sources and sinks for pollutants, respectively[18]. When switching their locations without change of their sizes, the impact of landscape pattern on non-point source pollution may change substantially, but the indices such as patch area index and diversity indices keep unchanged. Hence, it is necessary to build sound relationships between spatial pattern and ecological processes, and develop methods which can effectively reflect the relationships and their dynamics.

In China, lots of ecologists have tried to link spatial pattern to ecological processes[10,48,50–52]. Fu *et al*.[53] as well as Zhao *et al*.[54] built multi-scale landscape evaluation index for the Loess Plateau, which suffers serious soil erosion. Zeng *et al*.[55] detected the fragmentation in mountain forest landscape based on boundary characteristics. Li *et al*.[56,57] soundly analyzed rocky desertification in Karst area of China. Li *et al*.[58] and Liu *et al*.[59], respectively, studied the effects of wetland landscapes on nutrient reduction and its fragmentation on habitat of water birds. All the studies set good examples for determination of pattern-process relationships, but the exploration of ecological meanings for landscape indices needs to be further strengthened.

2.3 How to apply Patch-Corridor-Matrix theory to address practical problems?

Patch-Corridor-Matrix theory is a classical conceptual model presented in the earlier stage of landscape ecology, which is the basis of spatial pattern analysis. But how to apply this theory in practical use, and how matrix, patch and corridor with different proportions and distribution patterns affect ecological processes are lack of examples. Before applying Patch-Corridor-Matrix theory into practices, 4 problems should be solved: (1) what role does every single landscape element play in a certain ecological process? (2) Are there any differences in considering landscape components as matrix, patch or corridor? Does the effect of landscape component identification on processes change accordingly? (3) If the arrangement of landscapes as matrix, patch and corridor changes, will their effect on processes change accordingly? How to link Patch-Corridor-Matrix with ecological processes? (4) For a certain process, is there an optimum Patch-Corridor-Matrix pattern and how to find it?

3 Future of landscape pattern analysis

Landscape pattern is usually considered the result of various ecological processes at different scales, and the aim of landscape pattern analysis is to characterize the interactions between landscape pattern and ecological processes. At a certain spatiotemporal scale, using a series of ecologically meaningful landscape indices to quantify the heterogeneity of a landscape, and building sound relationships between spatial pattern and ecological processes to interpret interactions between pattern and processes are main tasks for landscape ecologists. Landscape ecology is a newly integrated discipline[19], and theories and methods from other fields of science can be introduced into this discipline. For further development of landscape pattern analysis, 5 areas should be addressed.

3.1 To develop a methodology quantifying both static landscape pattern and pattern dynamics

Landscapes, represented by land use maps, vegetation maps or landscape type maps interpreted with remote sensing images, are all static. Landscape indices calculated with these maps can only reflect landscape characteristics at a certain moment. However, ecological processes are always dynamic, and they usually last for a period of time, for example, a season or a year. It is unreasonable to link landscape indices calculated from a static landscape to dynamic processes.

Dynamic processes are concrete realities, therefore, to link pattern to processes, it is necessary to give dynamic attributes to landscape pattern. This can be achieved througth 3 approaches: (1) combining static landscape pattern as time sequences, that is, to combine land use/cover maps obtained in different times as a time series, from which the dynamics of landscape metrics can be obtained; (2) combining static landscape pattern with key factors affecting ecological processes: a given landscape pattern, the initial background for an ecological process, can be attached with dynamic attributes if the temporal change characteristics of key factors affecting ecological processes are combined with the initial landscape pattern; (3) establishing relationships between landscape pattern and ecological processes with the aid of dynamic TUPU. The method in TUPU can be used to establish TUPU patterns that reflect ecological process dynamics such as the change of vegetation index or the temperature/rainfall. Based on this, some mathematical expressions or paradigms for the relationship between different landscape patterns and the TUPU pattern of ecological processes can be formulated with pattern recognition approach, and then interactions between landscape pattern and ecological processes can be investigated accordingly.

3.2 To explore the ecological meaning of landscape pattern using a set of landscape indice

Using a set of landscape indices to depict landscape characteristics has gained much progress. However, most studies focus on landscape patterns without considering ecological processes, and the landscape index sets obtained from different landscapes differ greatly. Landscape index sets are needed in future spatial pattern analysis, which can not only reflect the whole features of landscapes, but also relate to ecological processes. Again, it is essential to establish a standard procedure for calculation of landscape indices, especially with remote sensing images before the selection of a set of landscape indices.

Different kinds of landscape metrics reflect different features of a landscape, such as indices describing numbers of landscape unit classes, shapes or distribution patterns of landscape components. A set of different landscape indices reflect various aspects of landscape features, but it is vital to make sure that all indices in the set are ecologically meaningful.

3.3 To develop new methods for process-oriented landscape pattern analysis

In a sense, the present spatial pattern analysis only describes characteristics of static landscapes, but ecological processes are always related to various factors. Therefore, it is unreasonable to link the landscape indices only reflecting static landscape characteristics to ecological processes. A process-oriented landscape metric formulation approach should be established with sufficient consideration of the target's ecological process and its key influencing factors that can have important impacts on or be impacted by landscape pattern.

Ecologically process-oriented landscape pattern analysis has received more and more attention. The landscape pattern analyses pertinent to species migration, urbanization and soil loss have increased gradually. Unfortunately, except for several indices such as connectivity index and LCI, landscape indices linking spatial pattern to ecological processes are still scant. Hence, it is in urgent need to build, verify and apply ecologically process-oriented landscape indices or indices formulated with proper consideration of key factors affecting ecological processes for the advancement of landscape research.

3.4 To conduct multi-dimensional landscape pattern analysis

Present landscape pattern analysis mainly focuses on lateral and temporal dimensions, while vertical dimension is also very important. For example, elevation and slope affect soil and water loss as well as species migration. Thus, landscape information at vertical dimension should also be integrated into landscape pattern analysis whenever necessary.

Two aspects should be considered when conducting multi-dimensional spatial pattern analysis: (1) Vertical change of landscape elements (such as land use/cover, vegetation type and leaf area index). Landscape pattern analysis without considering such changes along topographical gradients such as elevation and slope is often less convincing and hard to relate to ecological processes. (2) Different combinations of landscape elements in the vertical dimension. Landscape pattern usually mentioned is just land use/cover; however, other elements such as bed rock, soil and topography are all impact factors of landscape pattern. Therefore, involving vertical combinations of landscape elements into multi-dimensional landscape pattern analysis could be more practical.

3.5 To explain the relationship between landscape pattern and ecological processes by multi-scale pattern analysis

Choosing proper scales is an important step for landscape pattern analysis[3,60]. Only if appropriate scales are determined, studies on interactions between landscape pattern and ecological processes can make sense. Multi-scale pattern analysis can be achieved by 3 means: (1) using remotely sensed multi-resolution images to characterize landscape patterns. Images with different resolutions reflect landscape features at different scales. Landscape metrics obtained from these images can be organized as a sequence, which may better represent changes of landscape features when scale varies. (2) Changing grain sizes in an image, and using landscape indices calculated from the image with different grain sizes to characterize landscape pattern. (3) Using landscape indices obtained from an image with different extent sizes to represent landscape pattern characteristics. In all, through multi-scale pattern analysis, series of curves can be built for landscape indices, which change with data sources, grain or extent changes, and these curves could be linked to some target's ecological processes.

The development of landscape pattern analysis has made strong push for the advancement of landscape ecology, and it will still be an important part of landscape ecology in a long time period in the future. However, the development of pattern analysis theories and methodological tools such as landscape metrics is a difficult and urgent task for landscape ecologists. The five issues addressed above may be the future directions for landscape pattern research.

Acknowledgements

The project was financially supported by Key Project of CAS Knowledge Innovation Program （No. kzcx2-yw-421）, and National Natural Science Foundation of China (No. 40621061; 30570319)

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