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Landscape Ecology: Coupling of Pattern, Process, and Scale

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Abstract: Landscape ecology provides new theoretical frameworks and methodologies for understanding complex ecological phenomena at multiple scales. Studies of landscape ecology focus on understanding the dynamics of ecological patterns and processes, and highlight the integration of multiple disciplines. In this paper, we discussed the problems and challenges that landscape ecology is currently facing, emphasizing the limitations of current methods used to describe dynamic landscape patterns and processes. We suggested that the focus should be on the integration of ground-based observation, mobile monitoring, transect survey, and remote-sensing monitoring, as well as improved coupling of experimental and model simulations. In addition, we outlined the research frontiers in landscape ecology, including scaling, integrated pattern and process modeling, and regional synthesis. Lastly, a brief review of pattern-process-scale coupling studies in China was provided. We concluded by pointing out that pattern-process-scale interactions, correlations between natural, economic, and social processes, and the coupling of human and natural systems will be major research areas in landscape ecology in the future.
Keywords: landscape ecology; pattern and process; scale; integrated model; regional synthesis research

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1 Introduction

In landscape ecology, ′pattern′ generally refers to a spatial pattern, including the type, number, spatial distribution, and allocation of the components of landscape, and ′process′ focuses on the dynamic features of the occurrence and evolution of incidents or phenomena. The interaction between pattern and process is a core subject in landscape ecology. To understand pattern-process interactions, researchers must consider related issues such as the features and dynamic changes of landscape structure and function, as these are the driving forces and mechanisms of pattern and process changes. The structure and function of the landscape are interdependent and interact with one other, and both may change over time.

Given the complexity of landscape processes, one of the major offerings of landscape ecology is to address ecological issues at multiple scales by considering physical, chemical, and biological factors. For instance, the geographical distribution of terrestrial plants is mainly controlled by physical factors such as rainfall, topography, soil texture, and structure; at the same time, the distribution characteristics are also subject to biological factors such as competition for nutrients among different plants and interactions between plants and animals. In general, the structural characteristics of a larger landscape are dependent on non-biological factors such as climate, geological, and geomorphologic conditions, while factors such as animal activities, interactions between plant and soil, and human disturbances affect the formation of smaller landscape structures. Therefore, scaling is a hot topic in studies of landscape ecology because it is critical in understanding the ecological processes at various scales.

The concepts of consolidation and integration are increasingly emphasized in landscape studies. As Wu and Hobbs (2002) noted, although the landscape studies of

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North America have traditionally tended to focus on natural landscapes, researchers have become increasingly concerned with the effects of human activities on landscape formation. Many scientists have recognized that socio-economic processes are becoming more important in driving the changes of land use and land cover, and ultimately affect the structure, function, and dynamics of landscapes.

In this paper, we first identified the major problems and challenges of landscape ecology. We then discussed the research frontiers of synthesis studies in landscape ecology (i.e., scaling, integrated pattern-process modeling, and regional synthesis). A brief review of pattern-process-scale studies in China was also provided. We concluded by proposing the major research areas in landscape ecology in the future.

2 Problems and Challenges

To deal with the global problems of resource depletion and environmental deterioration, landscape ecology, as the study of the relationships between humans and the environment at multiple scales, should focus on broader, more complex environmental problems by consolidating and integrating natural, social, and economic factors. At present, major problems constraining further development of landscape ecology include: 1) insufficient field surveys, 2) poor continuous field observations and comparative experiments, 3) insufficient integration of remote sensing and ground-based surveys and observations, 4) a lack of approaches for regional synthesis and scaling, 5) poor process study and model development, and 6) a lack of cross-disciplinary studies.

The most frequently used tools in studies on landscape patterns include spatial statistical analysis, pattern indices analysis, and pattern dynamic modeling. The methods of spatial analysis include Moran′s I index, Geary′s C index, semi-variance analysis, trend surface analysis, blocked quadrant variance analysis, spectral analysis, wavelet analysis, Lacunarity analysis, and so on. The landscape indices, which are used to quantify landscape patterns, can be divided into two categories: landscape elements and landscape levels. The landscape elements include patch area/density/edge metrics, proximity/isolation metrics, boundary shape metrics, and contagion/interspersion metrics, and the landscape levels consist of diversity metrics beside the four above-mentioned indices (Chen *et al*., 2008). The most frequently used pattern dynamic models include the random model, Markov model (based on transition probability), and cellular automata (based on neighborhood rules). Great achievements have been obtained using various methods for studying landscape patterns. However, these methods have critical restrictions for further application due to the lack of interpretation of their ecological and geographical meanings. As Li and Wu (2004) pointed out, researchers often ignore the internal ecological meanings or make simple assumptions regarding the design of landscape indices in order to simplify the calculations. Similarly, the models only simulate and predict the pattern dynamics by identifying the transition probability or neighborhood rules, ignoring the role of ecological processes. Taking the cellular automata model as an example, its simplified structure can not capture the interactions among local individuals, although the rules of the model are based on a local scale. Nor can it detect the impacts of the factors of regional or global scales.

For studies of ecological processes, the methods include field observations, control simulations, and simulation modeling. Due to the constraint of experimental conditions, most field observations for ecological process studies are limited to a single scale or smaller scales. However, as multi-scale is one of the most significant characteristics of an ecosystem (Wu and Li, 2006), insufficient representation of the ecosystem by single- or limited-scale observations often leads to misleading results. As for the control of simulated experiments, the experimental design may be oversimplified or may deviate from actual processes due to the knowledge limitations of the researchers in their disciplinary backgrounds, which can make the simulation results unreliable or inaccurate. In terms of simulation models, the model parameters are usually based on small scale processes, so the major problem in applying these models is the integration of spatial heterogeneity at relatively larger scales.

In summary, applying each of the current methods alone in the study of landscape patterns and processes is not sufficient to ensure the frequency, accuracy, or quality of data; nor can they fully describe the patterns, changes, and internal features of the complex ecological and socio-economic processes. The integration of the methods, including ground-based observation, mobile observation, survey of transects, remote-sensing monitoring, and the coupling of experiment simulation and model simulation, is essential and necessary to push forward landscape studies.

3 Frontiers and Perspectives

Synthesis research is a promising gateway for addressing complex natural-social-economic issues in landscape ecology. The major topics may cover: 1) pattern and process coupling (e.g., landscape pattern and eco-hydrological processes, biogeochemical cycles, and interactive processes between human beings and land); 2) coupling of drivers, processes, and effects of land cover change (e.g., natural and socio-economic drivers, temporal and spatial changes, and effects on resources, environment, ecology, and disasters); 3) intra-regional and inter-regional heterogeneity (e.g., multi-disciplinary, regional synthetic experiments and research, regional methods and models, and intra-regional landscape diversity); 4) scaling (e.g., upscaling from population, community, and ecosystem to landscape, regional, and global scales, respectively); 5) synthesis research on natural, social, and economic processes (e.g., environmental change and planning, land use change and planning, and regional sustainable development); 6) model development (e.g., the application of nonlinearity and complexity science in landscape ecology, the development of landscape ecological process models and coupled pattern and process models, and validation of the model′s effectiveness); and 7) landscape ecological application (e.g., management of water resources, adaptation to climate change, ecosystem restoration and protection, regulation of land degradation, and strategy formulation for harmonious development between humans and nature).

3.1 Scaling

Scaling refers to the transformation of information across different temporal, spatial, or organizational scales, including upscaling and downscaling (Wu and Li, 2006). Scaling is the core of landscape ecology, which provides the basis for understanding and predicting complex ecological processes.

Generally, upscaling can be achieved through two steps: identification of the scale and transformation of cross-scale information. The first step involves the identification of multi-scales and the scale characteristics of the spatial patterns, which provides the basis for the next step. The tools that are commonly used for identifying the scale mainly include spatial statistics, methods of landscape indices, and fractal dimension analysis (Zhang, 2006). It should be noted that, although many tools for scale identification have been developed, the selection of the scale for observation is still subjective and thus introduces great uncertainties. For example, in studying the spatial distribution of birds′ nests, variables such as nest height and orientation are usually observed at the tree scale. However, these data have neither scale nor spatial significance. As a consequence, upscaling based on the tree-scale data cannot be simply explored at larger scales, such as a patch scale with different sizes and types. The best approach is to ′define′ the scale before making observations or measurements using scale identification tools and taking full consideration of the biological features of the parameters of interest (Wheatley and Johnson, 2009).

The second step is data extrapolation with specific models or methods of mathematical physics. Overall, there are four approaches of scaling: spatial analysis, similarity-based upscaling, local dynamic modeling, and random modeling (Zhang, 2007). However, the categorization of the methods may need further improvement. For example, the fractal dimension analysis in spatial analysis and the spatial allometry method based on similarity can be applied to the same scale domain and structurally expressed in the same type of formula as follows:

$$A = kB^D \tag{1}$$

where A is a landscape property; B is the measure of scale, such as patch size or length of a window in analyzing a landscape map; k is a constant; and D is fractal dimension or scaling exponent. The parameter A has almost the same meanings but different temporal or spatial characteristics at different scales. Then, what is the internal relationship between the scale characteristics of the parameter? Is there any possibility for developing new methods or using new method categorization?

Many ecologists have attempted to improve the upscaling methods from site to regional scales or to develop relevant models (Table 1). Of particular note is the theory and application of SATECO model proposed by Muraoka and Koizumi (2009). Conducting long-term research on the carbon cycle of a deciduous broad-

Table 1 Methods of observation and research from site to regional scales

Scale	Observation method	Research method
Region	Remote sensing	Data integration of multi-methods and multi-scales
Landscape	Transect observation	GIS technique
		Observation data
		Spatial modeling
		Dynamic simulation system
Site	Fixed location observation	Mechanism analysis of function and process
	Control experiment	

leaved forest ecosystem in Takayama, Japan, Muraoka and his team developed an upscaling method to extrapolate the carbon balance from the scale of plant leaf to canopy, stand, landscape, and ultimately the regional scale based on site and remote-sensing observations.

3.2 Integrated modeling of patterns and processes

Interactions between landscape patterns and ecological processes have been the focus and hotspot since the beginning of the study of landscape ecology (Fridley *et al*., 2007; Bisigato *et al*., 2009; Claessens *et al*., 2009). It is the complicated interactions between biological and non-biological processes at different scales that lead to landscape heterogeneity in space and time. Thus, the interactions between landscape patterns and ecological processes are the prerequisites for understanding the landscape complexity. Ignorance of either aspect will lead to incomplete understanding of landscape properties (Lu *et al*., 2007). Therefore, it is essential to integrate ecological patterns and processes in landscape studies.

At a relatively small scale, the coupling of patterns and processes can be realized through field observations (Fu *et al*., 2010). For instance, the interaction between the spatial distribution of soil nutrients and rainfall processes can be monitored at the slope scale. Nevertheless, direct observation, in most cases, is hard for large-scale studies due to time and budget limitations. For this reason, modeling has become a key research tool in pattern-process studies at larger scales.

A model is a simplified and abstract representation of a real system, and is composed of a set of components as well as their internal connections (Odum, 2000). Currently, two types of landscape models are used in the study of pattern-process interactions (Schröder and Seppelt, 2006). The first type of model, which includes wavelet analysis, the habitat distribution model, and the neutral model, is based on pattern description and landscape analysis to deduce potential processes and estimate parameters; the second type of model, such as the Patuxent watershed model, is based on describing processes to generate simulations of landscape patterns.

An observed pattern is only a visible expression captured by human eyes; however, the spatial and temporal variations of ecological processes (including disturbances) and their interactions may produce various patterns which are not detected by researchers. All of these factors make it very difficult for the pattern-based models (first type) to predict the underlying ecological processes. Therefore, the process-based models (second type) are more widely used (Childress *et al*., 2002; Schaldach and Alcamo, 2006; Ferrier and Drielsma, 2010). The process-based models propose a series of driving forces in the assumptions and synthetically consider the interactions between the landscape elements and process parameters (such as soil properties or climatic features), as well as the interactions among specific processes of various landscape elements (surface runoff or species competition). The Patuxent watershed model is one example of a process-based model, and integrates hydrological, geomorphologic, and ecological processes (Voinov *et al*., 2007a; 2007b; 2007c; 2007d). By linking nutrient dynamics, socio-economic, and other natural processes with land use change, the model can be used at various scales and provide policymakers with ecological and socio-economic information under different land use scenarios. However, the simulated patterns need to be calibrated, and the primary difficulty may relate to obtaining observed data.

3.3 Regional synthesis research

In landscape ecology, pattern, process, and scale are three general perspectives from which the complexity of nature is studied. The objective of studying natural complexities at a regional scale is to summarize the interactions between the pattern and process in addition to their scale effects. Therefore, regional synthesis research must be based on a full understanding of the single factor and process within the lower scales. It also provides new perspectives and proposes new demands for studies on pattern-process interactions, which at the same time promotes its own development (Zhang *et al*., 2009). Regional synthesis research involves the coupling of multiple scales, factors, and processes as well as the integration of multiple disciplines.

Firstly, regional synthesis research involves integrating different ecological factors and processes (Ni, 2003). For example, eco-hydrology, a burgeoning discipline in recent decades, focuses on the functional relationships between hydrological and biological processes (i.e., on one hand, the impacts of vegetation cover and land use on hydrological processes such as runoff, evaporation, and change of water quality, and on the other hand, the impacts of hydrological behaviors on vegetation growth and distribution). At the same time, some abiotic factors related to the water environment (such as wetlands and riversides) and some biotic factors (such as plants and animals) are also involved with the interactions and feedback among ecological and hydrological processes (Hannah *et al*., 2004). In the contemporary era, many environmental problems are not caused solely by natural processes; humans play an important role in the landscape, even on larger scales. It is increasingly essential to include economic and social factors in regional synthesis research.

However, it is not easy to conduct synthesis research because researchers with different backgrounds often consider the same issue from their own perspectives and use only methods they are familiar with (Hannah *et al*., 2007). As Daly and Farley (2004) stated, it is better to include experts from various disciplines and encourage collaborations from the beginning of a project rather than to combine the results from several individual studies. Such a combination of results is only a ′pastiche′ that lacks effective information communications in resolving individual issues. In this sense, as ′Rome is not built in a day′, it may take a long time to truly integrate the disciplines. This will require researchers to expand their horizons and fully understand the mechanisms behind the research questions they pose.

4 Coupled Pattern-process-scale Studies in China

In recent years, the coupling of pattern, process, and scale has been increasingly emphasized in landscape ecology in China. Some related studies that are based on direct observations include the effects of urbanization or agricultural development on biodiversity, structure, mating pattern and seed production of urban forests, and the pattern and nutrient retention of wetlands (Li *et al*., 2005; Yin *et al*., 2009; Wang *et al*., 2010a; Xu *et al*., 2010; Zhang *et al*., 2010), the effects of natural fires on forest structure (Kong *et al*., 2005), and the effects of land use/cover change on soil, water, nutrient dynamics (Fu *et al*., 2000; Wang *et al*., 2010b), and hydro-ecological processes (Wang *et al*., 2006). For the pattern-process studies that are based on modeling approach, a representative one is the ′source-sink′ landscape model, which is used to simulate non-point pollution or soil-water loss (Chen *et al*., 2003). The LANDIS model is used to simulate the effects of harvesting and planting, and fire exclusion on forest structure (Chang *et al*., 2007; Bu *et al*., 2008). Most other integrated modeling studies are realized by connecting existing model components via a spatial analysis platform such as GIS software (Xu *et al*., 2009).

Regional synthesis is also conducted, particularly in areas with special regional characteristics. For example, water and soil loss is the most serious environmental problem in China, particularly in the Loess Plateau area. Great achievements have been made in the study of interactions between water-soil loss and land use/cover change at different scales (including patch, slope, and watershed scales) and their scale effects (Fu *et al*., 2002; 2006; Wang *et al*., 2006; Wei *et al*., 2007; Fu *et al*., 2009) in this region. Researchers have found that different factors such as soil properties, climate, landform, land use, and disturbance play different roles at varied scales. In addition to natural causes, socio-economic factors are considered as indirect drivers (Lu and Stocking, 2000; Su *et al*., 2011). Another example of regional synthesis research is the study on the Karst area in China. The hydrological cycle of the Karst area is quite different from other land areas due to its unique physiognomy with high spatial heterogeneity (Bonacci *et al*., 2009). Under natural conditions, the dynamics of the underground water is subject to the impacts of factors such as the solubility of rocks, water flow speed, and soil cover. With rapid economic growth and population increase, intense human activities such as agricultural irrigation and mining have become important factors that affect underground water (Jiang *et al*., 2009; Shi *et al*., 2009; Zhao *et al*., 2010).

5 Conclusions

Landscape ecology highlights the dynamics of ecological patterns and processes as well as the integration of multiple scales and disciplines. With socio-economic progress and the growing roles of humans in shaping the natural environment, the integration approach of landscape ecology will play an increasingly important role in meeting the challenges of globalization and sustainable development. Topics such as pattern-process-scale interactions, correlations between natural, economic, and social processes, and the coupling of human and nature systems will become major research areas in the field of landscape ecology.

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