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Key issues and research priorities in landscape ecology: An idiosyncratic synthesis

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Abstract

Landscape ecology has made tremendous progress in recent decades, but as a rapidly developing discipline it is faced with new problems and challenges. To identify the key issues and research priorities in landscape ecology, a special session entitled "Top 10 List for Landscape Ecology in the 21st Century" was organized at the 16th Annual Symposium of the US Regional Association of International Association of Landscape Ecology, held at Arizona State University (Tempe, Arizona, USA) during April 25–29, 2001. A group of leading landscape ecologists were invited to present their views. This paper is intended to be a synthesis, but not necessarily a consensus, of the special session. We have organized the diverse and wide-ranging perspectives into six general key issues and 10 priority research topics. The key issues are: (1) interdisciplinarity or transdisciplinarity, (2) integration between basic research and applications, (3) Conceptual and theoretical development, (4) education and training, (5) international scholarly communication and collaborations, and (6) outreach and communication with the public and decision makers. The top 10 research topics are: (1) ecological flows in landscape mosaics, (2) causes, processes, and consequences of land use and land cover change, (3) nonlinear dynamics and landscape complexity, (4) scaling, (5) methodological development, (6) relating landscape metrics to ecological processes, (7) integrating humans and their activities into landscape ecology, (8) optimization of landscape pattern, (9) landscape sustainability, and (10) data acquisition and accuracy assessment. We emphasize that, although this synthesis was based on the presentations at the "Top 10 List" session, it is not a document that has been agreed upon by each and every participant. Rather, we believe that it is reflective of the broad-scale vision of the collective as to where landscape ecology is now and where it may be going in future.

Introduction

In the past two decades, landscape ecology has experienced rapid and exciting developments in both theory and applications, and has transformed from a "regional" discipline practiced mainly in central and eastern Europe to a "global" science with its presence found in university curricula and a variety of ecological applications. With the recent and unprecedented advances, landscape ecology has been enriched and diversified greatly in theory, methodology, and applications. This is evident as one browses through the few dozens of books in landscape ecology published in less than a decade (e.g., Haines-Young et al. (1993), Naveh and Lieberman (1994), Forman (1995), Hansson et al. (1995), Zonneveld (1995), Bissonette (1997), Ludwig et al. (1997), Nassauer (1997), Farina (1998, 2000), Barrett and Peles (1999), Klopatek and Gardner (1999), Mladenoff and Baker (1999), Sanderson and Harris (2000), Wu (2000), Dale and Haeuber (2001) and Turner et al. (2001)). While a number of different definitions of "landscape" and "landscape ecology" can be found in existing literature, a sample of views from some prominent scientists in this field (Wiens and Moss 1999) confirmed the proliferation and divergence of per-

Table 1. Participants in the special session, "Top 10 List for Landscape Ecology in the 21st Century", at the 2001 Annual Symposium of US-IALE held at Arizona State University, Tempe, Arizona, USA, April 25–29, 2001.

Jack Ahern	Department of Landscape Architecture and Regional Planning, University of Massachusetts, Amherst, USA
Marc Antrop†	Department of Geography, University of Ghent, Belgium
Bill Baker	Department of Geography and Recreation, University of Wyoming, Laramie, USA
Gary and Terry Barrett	Institute of Ecology, University of Georgia, Athens, USA
Virginia Dale	Environmental Sciences Division, Oak Ridge National Laboratory, Oak Ridge, USA
Almo Farina	Faculty of Environmental Sciences, The Urbino University, Urbino, Italy
Richard Forman	Harvard University, Graduate School of Design, Cambridge, USA
Richard Hobbs†	School of Environmental Science, Murdoch University, Murdoch, Australia
Tony King†	Environmental Sciences Division, Oak Ridge National Laboratory, Oak Ridge, USA
Simon Levin†	Department of Ecology and Evolutionary Biology, Princeton University, Princeton, USA
Arthur Lieberman†	Professor Emeritus of Physical Environmental Quality at Cornell University, Ithaca, USA
David Mladenoff	Department of Forest Ecology and Management, University of Wisconsin, Madison, USA.
Zev Naveh	Israel Institute of Technology, Haifa, Israel
Bob O'Neill†	Oak Ridge National Laboratory, Oak Ridge, USA
Monica G. Turner†	Department of Zoology, University of Wisconsin, Madison, USA
John Wiens	Department of Biology, Colorado State University, Fort Collins, USA
Jianguo (Jingle) Wu	Symposium Organizer, Department of Plant Biology, Arizona State University, Tempe, USA

† Participants who sent in written lists, but did not give oral presentations at the meeting.

spectives and approaches. The recent diversification in landscape ecology has apparently caused some concerns with the "identity" of landscape ecology. As Wiens (1999) put it, "landscape ecology continues to suffer from something of an identity crisis". Moss (1999) warned that landscape ecology's "healthy, youthful development will be cut off before it matures if it does not recognize and develop its own distinctive core and focus".

Do we really need to be concerned with the identity of landscape ecology? What are, or should be, the "distinctive core and focus" of landscape ecology? Given the multidisciplinary origins of the field, should we embrace and solidify the interdisciplinarity of landscape ecology or move away from it? How do we integrate humans and their activities into landscape ecology, or should we at all? To move landscape ecology forward steadily and successfully in the 21st century, what are the priority issues? To address these questions, a special session, entitled "Top 10 List for Landscape Ecology in the 21st Century", was organized at the 16th Annual Symposium of the US Association of the International Association of Landscape Ecology (US-IALE) held at Arizona State University, Tempe, April 25–29, 2001. A group of leading landscape ecologists (Table 1) were invited to present their views on what the most important issues in landscape ecology are in the 21st century.

It was not surprising that the "Top 10 Lists" presented by the participants varied considerably in several ways in terms of their scope and specifics. Behind this seemingly overwhelming diversity and variability, however, some common themes did emerge from an arduous analysis and synthesis. To understand what the major issues in landscape ecology are according to the group of participants, we first sorted the presented materials into different categories, then tried to identify commonalities and differences, and finally reorganized them into two broad groups: (1) general issues characterizing landscape ecology as a scientific discipline and guiding its directions in future development, and (2) priority research topics defining the fundamental core and developmental fronts. While classification and synthesis are two common approaches to achieving a higher level of organization of information and, thus, understanding of complex phenomena, they inevitably have a certain degree of subjectivity introduced by the person who does the classification or synthesis. Here it is a case in point. Also, we note that the number of both key issues and research topics discussed below is reflective of the authors' logic of organizing information, not of the order of importance.

Key issues of landscape ecology

Interdisciplinarity or transdisciplinarity

All participants, one way or another, suggested that landscape ecology is and should be an interdisciplinary or transdisciplinary science. Currently, landscape ecology is more of a multidisciplinary endeavour, and cross-discipline fertilization and collaborations within and beyond the realm of ecology are needed to make it a truly interdisciplinary or transdisciplinary science. For many of the problems landscape ecologists deal with, they should work directly with landscape designers, planners and managers as well as social scientists and decision makers.

Integration between basic research and applications

Most participants indicated that landscape ecology should be an integrative science in which basic research and applications are fully integrated. Such integration should be reciprocal: research guides applications and applications feedback to research. At present, the degree of integration is far from being satisfactory. To enhance it, several activities have been suggested: developing research projects that deal with real-world problems; ensuring communication between landscape ecologists and practitioners (designers, planners, and resource managers), and presenting landscape ecology as a science of integrating theory and practice in university education. There is an urgent need for developing landscape ecological principles and pragmatic guidelines for applications in resource management, land use planning, and biodiversity conservation. On the other hand, the applications are necessary and essential to the development of a science core of landscape ecology. In general, as the behavior of complex systems like landscapes may not be predictable, some have suggested that landscape ecology should be perceived as more of an anticipative and prescriptive environmental science.

Conceptual and theoretical development

Landscape ecology is still lacking a generally accepted conceptual and theoretical basis on which principles, methods and applications can be developed. Naveh and Lieberman (1994) proposed that general systems theory, biocybernetics, and ecosystemology form the conceptual and theoretical framework for landscape ecology. However, this framework does not seem adequate to account for some recent theories, principles, and methods that deal explicitly with spatial heterogeneity. There seems to be an emerging view that the rapidly developing science of complexity (e.g., nonlinear dynamics, catastrophe theory, chaos theory, fractals, cellular automata, self-organization, hierarchy, complex adaptive systems) may provide a broader and, hopefully, sounder theoretical basis for landscape ecology. Also, for conceptual and theoretical developments, landscape ecology needs to go beyond "land" to include aquatic environments, and go beyond pecularities of specific landscapes to also seek generalities. Several important conceptual and theoretical topics are to be discussed in the next section.

Education and training

Education and training were considered one of the most important and pressing issues in landscape ecology by essentially all the participants. Comprehensive and integrative university curricula and professional training programs (within and outside academic institutions) in landscape ecology need to be established and strengthened. These curricula and training programs must emphasize the interdisciplinarity and holistic nature of landscape ecology, as well as the integration between science and applications. They also need to accommodate the diverse needs of students and professionals who have different interests and backgrounds.

International scholarly communication and collaborations

Several of the participants suggested that international communication and collaborations among landscape ecologists are important to the development of this field. Landscapes are shaped by physical and ecological processes as well as socioeconomic and cultural factors, and landscape ecologists are inevitably shaped by their science and cultural backgrounds and traditions. The exchange of ideas, methods, and interpretations of landscapes among ecologists and practitioners who are accustomed to different physical, socioeconomic, and cultural environments through communication and collaborations (e.g., forums, scholarly exchange programs, joint research projects) seems necessary for developing a comprehensive and coherent core of landscape ecology.

Outreach and communication with the public and decision makers

Almost all participants recognized that communication and outreach are a key to the success of landscape ecology in the decades to come. Effective communication between landscape ecologists and the public and decision-makers presently is lacking, but will be essential for the future development of the science and applications of landscape ecology. Communication is not only necessary to the integration between landscape ecological research and applications, but also can enhance the interdisciplinarity this field exemplifies. Effective communication with the public and people outside the "landscape ecology circle" requires willingness, desire, and commitment on the landscape ecologists' part. It may also entail a departure from the traditional way of doing science. Landscape ecologists need to be engaged and proactive in helping shape the landscape, while being scientifically honest and responsible. Advanced information technologies can certainly enhance communication, and outreach programs of different kinds should be promoted.

The six broad issues discussed above are all related to each other, and may be generally applicable to all interdisciplinary sciences (Figure 1). Developing a comprehensive and coherent scientific core may be most essential for the future of landscape ecology. This core is not likely to be adequate if it is merely a spatial expansion (larger-scale), or a spatialized version (considering space explicitly), of existing ecologies. Because the structure, functioning, and dynamics of landscapes are influenced by a myriad of physical, biological, socioeconomic, cultural, and political forces, it is evident that landscape ecology ought to be interdisciplinary in theory, methodology, and practice. Landscape ecology is expected to provide a scientific basis for resource management, land use planning, biodiversity conservation, and other broad-scale environmental issues, which makes the integration between basic research and applications even more essential than in other ecological disciplines. The interdisciplinarity and integration of landscape ecology reinforce each other. For example, landscape ecology provides a theoretical basis, as well as methods, tools, data and experiences, for landscape and urban planning and design, whereas the planned and designed landscapes may serve as field experiments to test hypotheses and theories in landscape ecology (Golley and Bellot 1991). While interdisciplinarity and integration characterize the field of landscape ecology, they must be accomplished through properly designed education and training programs, effective communication means and channels, and fertile collaborations of global reach.

Top 10 research topics

To develop a comprehensive and coherent scientific core of landscape ecology, it is useful to identify some of the major research topics. Based on the diverse views from the group, we have derived ten priority research topics that cover a wide range of theoretical, methodological, and applied issues. Recognizing that the reciprocal integration between theory and application is a salient characteristic of landscape ecology, we do not try to separate these topics into these three categories. It would also be difficult to do so because each topic needs to deal with the three aspects. However, some topics are more of theoretical or methodological developments, and some others highlight important areas of applications (Figure 2).

Ecological flows in landscape mosaics

A primary goal of landscape ecology is to understand the reciprocal relationship between spatial pattern and ecological flows or processes. This goal is far from being reached. While much of the attention has been given to spatial pattern analysis, research emphasis now should be directed towards processes themselves and how they affect, and are affected by, landscape pattern. Understanding the fundamental mechanisms and spatial dynamics and variability of ecological flows of materials (including organisms), energy, and information across landscape mosaics is central to landscape ecology.

In particular, the study of the interactions between population processes and spatial pattern has made much progress, but there is a need to integrate socioeconomic theory of landscape change into metapopulation models to make them more relevant to the issues of biodiversity conservation and landscape sustainability. The spread of invading species has become an increasingly important ecological and economic problem which deserves more research efforts. In addition, little is known about the interrelationship between spatial heterogeneity and ecosystem processes. For instance, how do ecosystem process rates

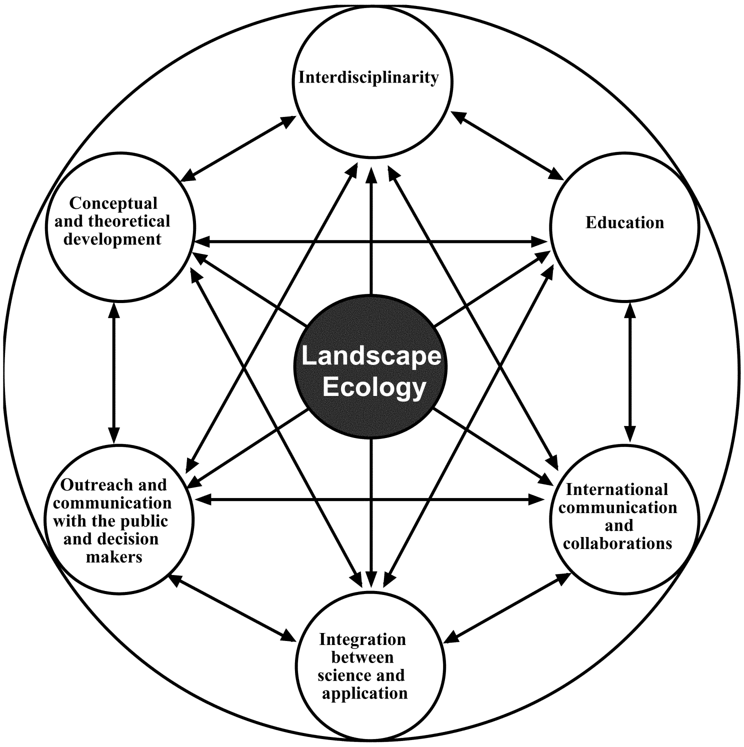


Figure 1. Six key issues in landscape ecology based on a classification of the presentations by the session participants. Interdisciplinarity and integration between research and application are two crucial issues identified by essentially all the session participants. The other four issues are all indispensable for an interdisciplinary and integrative science. The six issues and their interactions are important to sciences other than landscape ecology, but the emphasis on beyond-bioscience interdisciplinarity and real-world problem-solving seems one of the several characteristics distinguishing landscape ecology from the traditional bio-ecological disciplines such as population or community ecology.

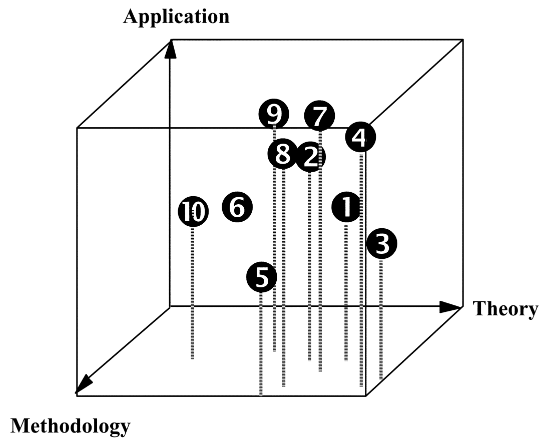
vary in space and across scales? What control such variations in diverse landscapes that are influenced by human activities with different characters and intensities? Apparently, integrating population, community, and ecosystem ecology into landscape ecology should be a high priority as well as an exciting challenge.

Causes, processes, and consequences of land use and land cover change

Land use and land cover predominantly determine the structure, functioning, and dynamics of most landscapes throughout the world. Land use and land cover change is driven primarily by socioeconomic forces, and is one of the most important and challenging research areas in landscape ecology, and indeed in global ecology. More research efforts are needed to understand the causes, processes, and ecological consequences of land use and land cover change. Landscape ecology needs to incorporate the insights of economic geography which studies how economic activity is distributed in space and resource economics which determines how land will be used (O'Neill 1999). Long-term landscape changes imposed by economies and climate change, as well as "land use legacies" (i.e., the types, extents, and durations of persistent effects of prior land use on ecological patterns and processes), need to be considered in the study of land use and land cover change. In addition, highly dynamic or chaotic landscapes (e.g., urbanizing landscapes or land areas under political, economic or military conflicts) may provide unique opportunities for studying land use and land cover change.

Nonlinear dynamics and landscape complexity

Landscapes are spatially extended complex systems in which heterogeneity, nonlinearity, and contingency are the norm. While emergent properties, phase transitions, and threshold behavior often characterize landscapes of all kinds, they are the manifestations of



1 Ecological flows in landscape mosaics
2 Causes, processes, and consequences of land use and land cover change
3 Nonlinear dynamics and landscape complexity
4 Scaling
5 Methodological development
6 Relating landscape metrics to ecological processes
7 Integrating humans and their activities into landscape ecology
8 Optimization of landscape pattern
9 Landscape conservation and sustainability
10 Data acquisition and accuracy assessment

Figure 2. Top 10 research topics in landscape ecology. All the topics need to address the issues of theory, methodology, and application. However, some of them focus more on theoretical or methodological developments, whereas others emphasize more on applications. The exact positions of the 10 topics in the 3-dimensional space are somewhat arbitrary, but a proper balance among the three components may be desirable in the study of each topic.

nonlinear dynamics of spatially heterogeneous systems. Ecological theories that can account for these characteristics need to be developed and tested. To effectively deal with the complexity of landscapes, insights from the science of complexity and nonlinear dynamics may play an important role. While Naveh and Lieberman (1994) emphasized the relevance of general systems theory, cybernetics, and nonlinear thermodynamics, only in recent years do we see a wide range of landscape ecological applications of concepts and methods from the science of complexity, particularly fractals and cellular automata. The science of complexity and nonlinear dynamics, with established and newly developing methods, may help the establishment of a theoretical and methodological basis for landscape ecology.

In supporting the above assertion, several participants advocated a number of concepts and theories in complexity science, including self-organization, complex adaptive systems (CAS), nonlinear dynamics, phase transition, and metastability. Levin (1999) has argued that ecosystems and biosphere are complex adaptive systems. In his view, heterogeneity, nonlinearity, hierarchical organization, and flows are four key elements of CAS that together allow for self-organization to occur. That is, CAS typically become organized hierarchically into structural arrangements through nonlinear interactions among heterogeneous components, and these structural arrangements determine and are reinforced by the flows of energy, materials and information among the components (Levin 1999). However, the theoretical potential and practical implications of studying landscapes as CAS are yet to be fully explored.

Scaling

Scaling refers to the extrapolation or translation of information from one scale to another in space and time. Most participants thought that scaling is most essential in both the theory and practice of landscape ecology. While scale effects are widely recognized in landscape ecology, questions are yet to be addressed of how to determine appropriate scales for understanding particular patterns and processes and how to scale up or down across heterogeneous landscapes. Specifically, how can information gained at fine scales be extrapolated to broad scales in space and time, or vice versa? How can knowledge at one organizational level be translated to another? How can results of experimental systems be extrapolated to real-world systems? What are the theoretical bases and pragmatic guidelines for aggregating and disaggregating data and variables in landscape ecological research? In the recent decades, there has bee a great deal of interest in scaling issues across all earth sciences, and the literature in this area is expanding rapidly. Yet, both general "rules of thumb" and specific techniques for scaling landscape patterns and processes need to be developed and tested more widely and rigorously. While the science of complexity may likely facilitate the search for scaling rules and strategies in landscape ecology, an integrated approach that combines field measurements, experimental manipulations, remote sensing, GIS, and modeling seems imperative for developing a science of scale.

Methodological advances

Many landscape ecological problems need to be studied over large and multiple scales in a spatially explicit manner. The spatial heterogeneity and complexity of landscapes pose new methodological challenges. For example, the lack of replicability at the landscape scale often results in the problem of "pseudoreplication" (Hargrove and Pickering 1992). Apparently, this creates a serious hurdle for using traditional scientific methods that hinge primarily on experimentation, although Oksanen (2001) has recently argued that this need not be as big a problem as is often stated. An integrative approach that combines observation, experimentation, and modeling seems necessary to deal with multi-scaled complex landscapes. The use of meta-analysis (the statistical synthesis of the results of separate studies) may also prove valuable. How these approaches should be mixed properly needs to be addressed in landscape ecological research.

Also, the ubiquitous existence of spatial autocorrelation in landscapes violates the fundamental assumptions of traditional methods in statistical analysis and data sampling and, thus, landscape ecologists need to be cautious and innovative when using statistical methods in experimental design and data analysis. At the same time, more attention should be given to the proper use, evaluation of effectiveness, and ecological interpretation of various spatial and geostatistical methods in landscape ecological research. Whatever techniques (GIS included) or methods are used, they must be preceded by, and aimed at, meaningful landscape ecological questions. We need to avoid having powerful methodologies in search of meaningful questions to answer; rather we need to seek the right techniques to answer pressing questions.

In addition, landscapes are often composed of physical, ecological, socioeconomic, and cultural patterns and processes. Most, if not all, of them are highly nonlinear complex systems whose behavior may be inherently unpredictable. This is especially true when human activities and processes must be considered essential to the system under study. Several participants suggested that more emphasis is needed for holistic and systems approaches as well as complexity theory and associated methods (e.g., self-organization, CAS, fractals, cellular automata, genetic algorithm, neural networks). To effectively deal with the methodological problems caused by spatial heterogeneity, lack of replicability, scale-multiplicity, autocorrelation, and interdisciplinary complexity, landscape ecologists may need to go beyond what traditional sciences can offer to invent new approaches. In particular, the traditional hypothetico-deductive doctrine is not adequate, and other scientific approaches need to be explored (e.g., Pickett et al. (1994)).

Relating landscape metrics to ecological processes

Many landscape metrics have been developed and widely used in the past two decades, but a sound technical and ecological understanding of these metrics is still lacking. For example, the basic question, how landscape metrics relate to ecological processes, remains largely unanswered. The claim that processes can be inferred by pattern needs to be critically examined in landscape ecological research. Clearly, the empirical relationships between pattern and process need to be better documented and the underlying mechanisms understood. Numerous studies have shown that landscape metrics are sensitive to changing scale (grain and extent), but are there general scaling functions across different types of landscapes? How much does a landscape need to change before a metric can detect the change? How does one determine whether or not changes in metrics are significant both statistically and ecologically? Is it possible to develop a set of standards for metrics selection and change detection? Can a suite of "vital landscape attributes" (Aronson and Le Floc'h 1996) be developed for monitoring and predicting landscape changes? How can we develop synthetic or holistic metrics that reflect social, cultural, and ecological diversity and heterogeneity? The above questions need to be addressed by combining both empirical and theoretical approaches. To make landscape metrics truly the metrics of landscapes, we must "get inside" the numerical appearance of metrics to find ecological essence, "move out" of the confines of the presumption that pattern must somehow be related to processes, and "go beyond" the patch-based metrics to incorporate other forms of heterogeneity.

Integrating humans and their activities into landscape ecology

Landscape ecology focuses on relatively large-scale ecological systems that are increasingly influenced and determined by human activities. As most of the participants unequivocally indicated, socioeconomic processes are the primary drivers for land use and land cover change which in turn determines the structure, function, and dynamics of most landscapes. Therefore, it is evident that humans themselves and their activities (be they rational or radical) must constitute an integral part of the ecology of landscapes, and they should be treated as such in research. It is becoming increasingly apparent that this is the case even in areas such as North America, where the emphasis on "natural" landscapes is slowly but steadily giving way to a perception of the importance of humans in shaping the landscape. In addition, the ideas relating to landscape planning and design need more careful interweaving with the biophysical aspects of landscape ecology, particularly if we aim to allow landscape ecology to be forward looking and to assist in preventing the recurrence of current land use dilemmas and designing landscapes for the future.

Thus, a more humanistic perspective is needed. In fact, landscape ecology, especially in Europe, has a tradition of considering humans and their activities as part of the whole landscape. In recent years, a "holistic landscape ecology" perspective–a systems view that links natural and human systems - has been advocated (Naveh and Lieberman 1994; Naveh 2000). The need for incorporating humans, including their perceptions, value systems, cultural traditions, and socioeconomic activities, into landscape ecology requires interdisciplinarity. As such, the reciprocal integration between basic research and applications has to be the norm, not just an ideal. Although some theories and methodologies exist, effectively integrating human-related processes into ecology may remain one of the ultimate challenges for ecologists and the like in the new century.

Optimization of landscape pattern

A fundamental assumption in landscape ecology is that spatial patterns have significant influences on the flows of materials, energy, and information while processes create, modify, and maintain spatial patterns. Thus, it is of paramount importance in both theory and practice to address the questions of landscape pattern optimization (e.g., optimization of land use pattern, optimal landscape management, optimal landscape design and planning). For example, can landscape patterns be optimized in terms of both the composition and configuration of patches and matrix characteristics for purposes of biodiversity conservation, ecosystem management, and landscape sustainability? Are there optimal ways of "spatially meshing nature and culture"? Are there ecologically optimum network forms? Research into the spatial optimization of landscape pattern for ecological processes may presents a new and exciting direction for landscape ecology. Such studies are likely to require theories and methods more than those in traditional operations research (e.g., different types of mathematical programming), as well as the participation of scientists and practitioners in different arenas.

Landscape conservation and sustainability

In view of the continuing human population growth and associated land use change and global environmental changes, the dynamic nature of landscapes is apparent and profound. Biological organisms and higher-level organizations composed of them live in increasingly fragmented landscapes. Thus, a paradox arises: on the one hand, the conservation and sustainability of landscape systems ought to be an ultimate goal of landscape ecology in action; on the other hand, such goal may not be attainable, especially, on large scales considering the persisting and pervasive changes. Most of the participants recognized the importance of applying landscape ecological principles in biodiversity conservation and maintaining the sustainability of landscapes. However, specific landscape ecological guidelines for biodiversity conservation are needed, and a comprehensive and operational definition of landscape sustainability is yet to be developed. Such definition may have to incorporate the physical, ecological, socioeconomic, cultural, and political components of the landscape, with explicit expression of scale in time and space. A related issue that is equally important and similarly challenging is to develop a scientifically justifiable basis and a set of pragmatic guidelines for valuing ecosystem services of landscapes. Such valuation must properly take into account the non-marketable and intangible aesthetic, cultural, spiritual, and non-instrumental intrinsic nature values. Although ecologists have been addressing the issue of sustainability primarily in terms of species and ecosystems, the reality is that how humans perceive and value landscapes will significantly influence both the science and practice of landscape sustainability.

Data acquisition and accuracy assessment

The availability and quality of data over large areas and extended time periods are critical to the development of landscape ecology because its research focus is usually on, but not restricted to, broad-scale patterns and processes. Indeed, it was no coincidence that giant strides in landscape ecology often occurred in the wake of technological advances in surveying and information-processing. Today, a suite of advanced technologies are readily available to landscape ecologists. For example, various remote sensing techniques provide continuous streams of digital information over large areas with multiple spectral, spatial, and temporal resolutions; evolving geographic information systems continue to revolutionize the way of storing, manipulating, and analyzing spatial data; and global positioning systems allow ecologists to get "spatial" quickly and accurately. Landscape ecologists as a whole are among arguably the best equipped "high-tech" ecologists today. But, "high tech" not only often comes with "high cost", but sometimes "high risk" as well. Several problems were identified concerning the acquisition, quality, and analysis of landscape data.

First of all, detailed biological understanding of organisms and species is essential to understanding many aspects of landscape structure and function, and this requires the collection of basic biological data on organisms and species. Second, the problems inherent in sampling across large regions in a way that permits inference of the effects of spatial heterogeneity remain challenging. Innovative sampling methods are needed, using appropriate (and possibly new) statistical methods and creative combinations of available methods, including field sampling, experimentation, remote sensing, and modeling. Third, the quality of landscape data is often unsure due to the lack of metadata, error/uncertainty analysis, and accuracy assessment. However, the quality of data and metadata will directly determine landscape ecologists' ability and effectiveness of detecting patterns and relating them to processes, and consequently affect research results and practical recommendations. Developing and testing methods of error/uncertainty analysis of landscape data and assessing the effects of data quality on the results of landscape pattern analysis and modeling represent an extremely important and challenging research priority. Fourth, to understand the structure, function and dynamics of landscapes requires time series of spatial data, which in turn call for long-term landscape monitoring programs. Landscape monitoring is not only essential for testing landscape ecological theories and principles, but also for maintaining landscape sustainability through adaptive strategies. A sound landscape monitoring program needs to be interdisciplinary in science, integrative in methodology, and multiple in scale.

Discussion

Since 1939 when the term, "landscape ecology", was coined by Carl Troll, the field has certainly made many gigantic strides in theory, methodology, and applications. In the same time, new problems and challenges are also abundant, begging for solutions. It is an important first step to identify what the priority issues and challenges are, and the special session on the Top 10 List for Landscape Ecology in the 21st Century was an attempt towards this end. There was a diversity of views made at the special session, which was due, in part, to the fact that there had not been a prescribed set of rules for the participants to produce their "lists". We realize that this synthesis paper is a result of "nonlinear" interactions among "fractal" components with one particular set of initial conditions. We are not sure that the "whole" in this case is necessarily larger than the "sum of parts", but it is certain that the whole is not exactly equal to the sum. Although several common themes seem clear to us, the details may not be agreed upon by all the participants. In addition, we acknowledge that neither the selection of participants nor the process of synthesis was based on a rigorous statistical design, thus the results reported here may not be reproducible or verified in that sense.

The title of John Wiens' presentation at the spatial session, "Looking ahead by looking back", seems to suggest a historical and dialectical way of conducting the science and practice of landscape ecology. Indeed, many of the important issues brought up at the special session have much to do with the history of landscape ecology. The early developments of landscape ecology took place mainly in the central and eastern Europe focusing on issues directly related to landscape planning, management, conservation, and restoration. This research emphasis on the interactions between human activities and land resources necessitated the development of holistic, interdisciplinary, and somewhat pragmatic views and approaches. In contrast, landscape ecology began to develop in North

America in the 1980s with an apparent emphasis on spatial heterogeneity and its effects on ecological processes where quantitative methods, particularly spatial pattern analysis and modeling, are central. The conceptual framework for the North America perspective is often traced back to Watt's (1947) seminal work on patch dynamics and MacArthur and Wilson's (1967) theory of island biogeography. In short, there have been two contrasting and complementary perspectives in landscape ecology: one is more humanistic and holistic and the other more bio-ecological and analytical.

However, this largely geographically-based dichotomy of the schools of thought is an oversimplification of the reality, and maybe has been exaggerated in view of the state-of-the-science of landscape ecology. Both perspectives have been practiced by ecologists worldwide, and the current trend is more of a convergence rather than divergence (Naveh and Lieberman 1994; Wu 1999; Wiens and Moss 1999; Turner et al. 2001). Developments in landscape ecology in recent years clearly indicate the necessity and feasibility of integrating these two perspectives into a more comprehensive one that is holistic and with scientific vigor. Naveh (1988) pointed that "One of the major challenges for landscape ecology is... to form a unified theoretical and methodological framework for a transdisciplinary science that is oriented to both problem-inquiry and problem-solving". Wiens (1999) also believed that "While many interdisciplinary approaches are simply traditional disciplines dressed in new clothes, "landscape ecology truly is interdisciplinary." Yet, how to do holistic and transdisciplinary research with acceptable scientific rigor remains a grand challenge to landscape ecologists and the like. Given the interdisciplinary and application-oriented nature of landscape ecology, as perceived by most of the participants, how well we meet this challenge has a major bearing on the future of the field.

The rapid diversification and inconsistency of ideas and approaches characterize most young and immature sciences (Kuhn 1970). While this is apparently the case with landscape ecology, diversity, rather than divergence, of perspectives may be a lasting hallmark of all interdisciplinary sciences. The current developmental stage of landscape ecology may be called a stage of discovery — somewhere between the infant stage and mature stage. It certainly has a number of characteristics of immature science, such as the lack of consistency and coherence in concepts and theories. As discussed above, landscape ecology is expected to be a genuinely interdisciplinary field that emphasizes reciprocal integration between theoretical developments and empirical testing and applications. Because of its scientific immaturity and because human activities and socioeconomic processes need to be considered as an integral part of the landscape under study, a dilemma often occurs which may hinder the integration between theory and application as well as interdisciplinary fertilization. The comment on scientific thought by Kuhn (1983) seems quite appropriate for describing this predicament: "There are policy decisions to which scientific findings are relevant, but for which these findings are not precise enough nor the theories developed enough to permit analysis of outcomes in any but the vaguest terms. If scientists then respond to pressure for definite, factual answers, they mislead policymakers. But if policymakers insist that only precise, factual answers will do, they reject the only help scientists can sometimes give" (cited in Putnam (1986)). On the one hand, such situation is apparently not unique to landscape ecologists. On the other hand, it is in the middle of this dilemma do we see great potentials of ecologists influencing landscapes! While the accuracy of the "top 10 lists" can not be certain — much like any projection of the highly nonlinear dynamics of complex landscapes, the challenges landscape ecologists have to face up are certainly grand and multifaceted.

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References

Aronson J. and Le Floc'h E. 1996. Vital landscpae attributes: Missing tools for restoration ecology. Restor. Ecol. 4: 377–387.

Barrett G.W. and Peles J.D. 1999. Landscape Ecology of Small Mammals. Springer-Verlag, New York, New York, USA.

Bissonette J.A. 1997. Wildlife and Landscape Ecology. Springer-Verlag, New York, New York, USA.

Dale V.H. and Haeuber R.A. 2001. Applying Ecological Principles to Land Management. Springer-Verlag, New York, New York, USA.

Farina A. 1998. Principles and Methods in Landscape Ecology. Chapman & Hall, London, UK.

Farina A. 2000. Landscape Ecology in Action. Kluwer Academic Publishers, Boston, Massachusetts, USA.

Forman R.T.T. 1995. Land Mosaics: The Ecology of Landscapes and Regions. Cambridge Univ. Press, Cambridge, UK.

Golley F.B. and Bellot J. 1991. Interactions of landscape ecology, planning and design. Landsc. Urban. Plan. 21: 3–11.

Haines-Young R., Green D.R. and Cousins S.H. 1993. Landscape Ecology and GIS. Taylor & Francis, London, UK.

Hansson L., Fahrig L. and Merriam G. 1995. Mosaic Landscapes and Ecological Processes. Chapman and Hall, London, UK.

Hargrove W.W. and Pickering J. 1992. Pseudoreplication: A sine qua non for regional ecology. Landsc. Ecol. 6: 251–258.

Klopatek J.M. and Gardner R.H. 1999. Landscape Ecological Analysis: Issues and Applications. Springer-Verlag, New York, New York, USA.

Kuhn T.S. 1970. The Structure of Scientific Revolutions. Univ. of Chicago Press, Chicago, Illinois, USA.

Kuhn T.S. 1983. Roundtable: Kuhn and Lederberg on Scientific Thought. New York Times, New York, New York, USA, March 13, 1983.

Levin S.A. 1999. Fragile Dominion: Complexity and the Commons. Perseus Books, Reading, Pennsylvania, USA.

Ludwig J., Tongway D., Freudenberger D., Noble J. and Hodgkinson K. 1997. Landscape Ecology, Function and Management. CSIRO, Collingwood, Australia.

MacArthur R.H. and Wilson E.O. 1967. The Theory of Island Biogeography. Princeton Univ. Press, Princeton, New Jersey, USA.

Mladenoff D.J. and Baker W.L. 1999. Spatial Modeling of Forest Landscape Change: Approaches and Applications. Cambridge University Press, Cambridge, UK.

Moss M.R. 1999. Fostering academic and institutional activities in landscape ecology. In: Wiens J.A. and Moss M.R. (eds), Issues in Landscape Ecology. International Association for Landscape Ecology, Snowmass Village, Colorado, USA, pp. 138–144.

Nassauer J.I. 1997. Placing Nature: Culture and Landscape Ecology. Island Press, Washington DC, USA.

Naveh Z. 1988. Biocybernetic Perspectives of Landscape Ecology and Management. In: Moss M.R. (ed.), Landscape Ecology and Management. Polyscience, Montréal, Québec, Canada, pp. 23–34.

Naveh Z. and Lieberman A.S. 1994. Landscape Ecology: Theory and Application. 2nd edn. Springer-Verlag, New York, New York, USA.

Naveh Z. 2000. What is holistic landscape ecology? A conceptual introduction. Landsc. Urban. Plan. 50: 7–26.

Oksanen L. 2001. Logic of experiments in ecology: is pseudoreplication a pseudo issue? Oikos 94: 27–38.

O'Neill R.V. 1999. Theory in landscape ecology. In: Wiens J.A. and Moss M.R. (eds), In Issues in Landscape Ecology. International Association for Landscape Ecology, Snowmass Village, Colorado, USA, pp. 1–5.

Pickett S.T.A., Kolasa J. and Jones C.G. 1994. Ecological Understanding: The Nature of Theory and the Theory of Nature. Academic Press, San Diego, California, USA.

Putnam S.H. 1986. Future directions for urban systems models: some pointers from empirical investigations. In: Hutchinson B. and Batty M. (eds), Advances in Urban Systems Modeling., New York, North Holland,, pp. 91–108.

Risser P.G., Karr J.R. and Forman R.T.T. 1984. Landscape Ecology: Directions and Approaches. Illinois Natural History Survey Special Publ. 2, Champaign, Illinois, USA.

Sanderson J. and Harris L.D. 2000. Landscape Ecology: A Top-Down Approach. CRC, Boca Raton, Florida, USA.

Troll C. 1939. Luftbildplan and okologische bodenforschung. Zeitschraft der Gesellschaft fur Erdkunde Zu, Berlin, 241–298.

Turner M.G., Gardner R.H. and O'Neill R.V. 2001. Landscape Ecology in Theory and Practice: Pattern and Process. Springer-Verlag, New York, New York, USA.

Watt A.S. 1947. Pattern and process in the plant community. J. Ecol. 35: 1–22.

Wiens J.A. 1999. Toward a unified landscape ecology. In: Wiens J.A. and Moss M.R. (eds), Issues in Landscape Ecology. International Association for Landscape Ecology, Snowmass Village, Colorado, USA, pp. 148–151.

Wiens J.A. and Moss M.R. 1999. Issues in Landscape Ecology in. International Association for Landscape Ecology, Snowmass Village, Colorado, USA.

Wu J. 1999. Hierarchy and scaling: Extrapolating information along a scaling ladder. Can. J. Rem. Sens. 25: 367–380.

Wu J. 2000. Landscape Ecology: Pattern, Process, Scale and Hierarchy. Higher Education Press, Beijing, China.

Zonneveld I.S. 1995. Land Ecology. SPB Academic Publishing, Amsterdam, The Netherlands.