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The Third and Fourth Dimensions of Landscape: towards Conceptual Models of Topographically Complex Landscapes

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Abstract

Relating spatial patterns to ecological processes is one of the central goals of landscape ecology. The patch-corridor-matrix model and landscape metrics have been the predominant approach to describe the spatial arrangement of discrete elements ("patches") for the last two decades. However, the widely used approach of using landscape metrics for characterizing categorical map patterns is connected with a number of problems. We aim at stimulating further developments in the field of the analysis of spatio-temporal landscape patterns by providing both a critical review of existing techniques and clarifying their pros and cons as well as demonstrating how to extent common approaches in landscape ecology (e.g. the patch-corridor-matrix model). The extension into the third dimension means adding information on the relief and height of vegetation, while the fourth dimension means the temporal, dynamic aspect of landscapes. The contribution is structured around three main topics: the third dimension of landscapes, the fourth dimension of landscapes, and spatial and temporal scales in landscape analysis. Based on the results of a symposium on this theme at the IALE conference in 2009 in Salzburg and a literature review we emphasize the need to add topographic information into evaluations of landscape structure, the appropriate consideration of scales; and to consider the ambiguity and even contradiction between landscape metrics.

Keywords:
Spatial patterns, landscape metrics, 3D-metrics, landscape dynamics, scale

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Introduction

Relating spatial patterns to ecological processes is one of the central goals of landscape ecology (Naveh and Lieberman 1990; Forman 1995; Wu 2006; Wu and Hobbs 2007). Pattern analysis of landscape structure or quantification of spatial heterogeneity is crucial for understanding the underlying ecological processes and dynamics (Forman 1995; Turner 1989; Scheiner 1992; McGarigal and Marks 1995; Gustafson 1998). Heterogeneity can be defined as the degree of spatial variability of some property within a system (Li and Reynolds 1995; Morgan and Gergel 2010). Which property of the system "landscape" is to be considered depends largely on the conceptual model of landscape. Under the influence of the prominent patch-corridor-matrix model (Forman 1995), the two-dimensional model of landscape seems to be the standard. Thus, in the preamble of his influential book, Forman (1995) stated "the land as seen from an airplane window or on aerial photograph is the subject of this volume". Consequently land cover is de facto the main (and only) landscape property used in quantifying the spatial heterogeneity of the system "landscape".

The patch-corridor-matrix model and landscape metrics have been the predominant approach to describe the spatial arrangement of discrete elements ("patches") for the last two decades (Antrop 2007; Li and Wu 2007; Kent 2009), leading to major advances in understanding landscape pattern-process relationships (Turner 2005).

However, this model largely neglects topographic gradients, which turn into the main drivers of landscape process, structure and, consequently, spatial heterogeneity outside flat landscapes. Thus, information on ecologically meaningful 3D-structures like land-surface shape or elevation is not considered, which could lead to biased results of landscape metrics applications in topographically complex landscapes (Dorner et al. 2002; Blaschke and Drăguţ 2003; Hoechstetter et al. 2008). As Dorner et al. (2002) pointed out "the theoretical framework of landscape ecology to date does not provide a well-developed methodology for analyzing pattern and dynamics in landscapes with strong topography". This observation still holds true.

Only recently, an alternative landscape model that opens the way to the third dimension of landscapes has been proposed. Thus, in the "landscape gradient" model (McGarigal and Cushman 2005) heterogeneity is accounted for as the variability of a three-dimensional surface, which can be represented by any ecological attribute of interest. Based on this model, surface metrics have been developed for the purpose of quantifying surface heterogeneity at the scale of entire landscapes (Hoechstetter et al. 2008; McGarigal et al. 2009). However, the dichotomy continuous vs. discrete is leading the discussion towards technical improvements, rather than to really new models of landscapes, more suitable for topographically complex areas.

Our goal is to stimulate further developments towards conceptual models of topographically complex landscapes. We hypothesize that in such landscapes homogeneity measures should rely on elevation and its derivatives besides land cover information. Therefore, we provide a critical review of existing techniques and their suitability in quantifying landscape heterogeneity, while looking at alternatives of extending the patch-corridor-matrix model, or even replacing it. Since heterogeneity is dependent upon both spatial and temporal scales of measurement (Wiens 1989), time and scale should be important parameters. Therefore the contribution is structured around three main topics: the third dimension of landscapes (e.g. the vertical dimension like the elevation, the relief and the height of vegetation), the fourth dimension of landscapes (e.g. temporal dimension or landscape dynamics), and scales in landscape analysis.

The paper is based on contributions to a symposium at the IALE-conference in Salzburg 2009. Table 1 shows the themes of the presentations and the posters and their respective foci. All oral presentations and three posters are available online.

Table 1. Lectures within the Symposium 6: The third and fourth dimensions of landscapes. IALE European Conference, Salzburg, 2009.

Title	Author	Focus & methods
1. The third dimension of landscapes		
3D-metrics in landscape ecology	*S. Hoechstetter*	Surface metrics/Review
Assessment of structural connectivity of a forested landscape in Poland using graph theory approach	*E. Laszczak*	Landscape metrics/Graph theory
Landscape Metrics Selection Based on the Mathematical Models of Landscape Patterns	*A. Victorov*	Landscape metrics/mathematical modeling
2. The fourth dimension of landscapes		
A Critique of patch-based landscape indicators for detection of temporal change in fragmentation	*J. Wickham*	Landscape dynamics/Review
The applicability of quantitative techniques for assessing spatio-temporal patterns of landscape changes	*V. Van Eetvelde*	Landscape dynamics/Change detection
Integrating historical maps and LiDAR Elevation Data for Landscape Reconstruction: a case Study in Flanders (Belgium)	*I. Werbrouck*	Landscape dynamics/Historical reconstruction
3. Spatial and temporal scales in landscape analysis		
Scale issues in landscape ecology research – a synthesis	*D. J. Marceau*	Scale/Review
A method to assess landscape functional connectivity at local scale for target species	*R. Scolozzi*	Landscape connectivity/Spatial graphs
Influence of landscape pattern on scale divergence in categorical maps	*E. Diaz-Varela*	Scale optimization/Multi-scale analysis

The third dimension of landscapes

The third dimension can play an important role in landscape ecology. Up to now, the majority of methods associated with the patch-corridor-matrix model, consider landscapes as two-dimensional surfaces mainly. Hoechstetter et al. (2008, 2009) presented several fundamental approaches for the integration of the third spatial dimension into landscape analyses. The developed so called "3D-metrics" delivers methods for instance for the integration of true surface area, perimeter and distance. Furthermore, indices derived from surface metrology and lacunarity analysis were adapted. Different case studies revealed the applicability of these methods for different purposes.

The assessment of structural connectivity using a graph theory approach was in the focus of the second speaker, Elżbieta Laszczak. She worked out that the graph theory is a widely applied framework in network analysis, but until now little attention has been paid to the consequences of assessing structural connectivity. In particular, polygon-to-point (habitat patch to graph node) conversion methods and distance metrics may have an impact on the results of connectivity assessments. In a case study, structural landscape connectivity within a forested landscape in Poland was assessed using different methods to build graph models. The research showed that graph construction methodology might result in several differences in the delineation of potential landscape corridors. Mathematical models for the selection of landscape metrics were presented by Alexey Victorov. He showed how the selection process of landscape metrics can be optimized. This is mainly achieved based on a new branch of landscape science, the mathematical morphology of landscapes. The selection of landscape metrics for different purposes can be carried out theoretically using mathematical models.

The fourth dimension of landscapes

Body of knowledge

Landscape ecology has been and still is very much concerned with the problems of understanding landscape elements, their composition and interrelations. This has gained a comprehensive body of knowledge and a more and more commonly agreed methodology based on an increasing amount of theoretical and empirical research. From the late 80ies (Forman and Godron 1986, o'Neill et al. 1988, Turner et al. 1989) throughout the 90ies (Forman 1995, McGarigal and Marks 1995, Haines-Young and Chopping 1996, o'Neill et al. 1996, Gustafson 1998, Hargis et al. 1998, Jaeger 2000), this body of literature evolved continuously into a commonly agreed methodology, maybe paradigm. But dealing with landscape elements, defining them, measuring and modelling their sizes, shapes and spatial distributions is only the very obvious frontside of an inherent and scientifically more difficult task: Landscape ecology deals with the problems of understanding, modelling and managing complex systems and processes in the physical environment. A number of approaches to landscape ecology have developed in East Europe, West Europe, North America and Australia earlier which are not repeated herein. This section elucidates the temporal dimension or the process dimension. Landscapes undergo development and are subject to change.

Lang et al. (2009) have succinctly summarized different qualities of changes, ranging from seasonal, cyclic changes (phenological course, crop rotation systems), through episodic, but still repetitive changes (e.g. forest fires, avalanches, foods and the like), to more pertinent changes, often directed by a trend. This trend may be caused by changing land use patterns due to changing climatic regime (e.g. desertification, decreasing average temperature) or especially economic-political changes such as for instance changes caused due to declining subsidy payments in agriculture. Changing landscape structures can be identified and quantified; they offer valuable hints for changing processes in the background. For instance, habitat fragmentation may lead to loss in biodiversity due to decline in dispersal space and limited possibilities for foraging or mating (Lang et al. 2009).

We may briefly distinguish two large groups of approaches:

1. Approaches that have in common methods based on the measurement of landscape structure for given snapshots in time. For simplicity, we call this 'time-sliced pattern'.
2. Approaches, which explicitly deal with processes, typically single processes such as hydrological or geomorphological processes or fluxes of material. We refer to this wide and heterogeneous group as 'process-based'.

The time-sliced pattern approaches

For the first group of approaches we can state that many authors, e.g. Haines-Young and Chopping (1996), Hargis et al. (1998), Gustafson (1998), Jaeger (2000), Moser et al. (2007) clearly worked out the great potential but also the limitations (see also Blaschke and Petch 1999, Li and Wu 2004, Corry and Nassauer 2005) of landscape metrics and the pointed at strong need to correlate the landscape indices to the phenomena under investigation and the strong need to understand what an index really measures.

From a literature review we hypothesize that patch-based metrics may sometimes be inappropriate for landscape change detection especially for the detection of temporal change in fragmentation (Wickham et al. 2007, see also Jaeger 2000, Moser et al. 2007, Li and Wu 2004), because patch-based metrics may (i) be difficult to interpret, (ii) lead to counterintuitive results, (iii) fix the observation scale, and (iv) not apply when the feature of interest is the matrix.

Summarizing the arguments from the literature study we can conclude that the landscape metrics based approaches are sophisticated today and serve various demands. Next to the discussed problems of scale etc. another potential for errors or misuse is the explicit or implicit multi-step interpretation.

With this, we refer to analysis of metrics, that is (i) understanding what they mean, (ii) assessing their properties, and (iii) assessing use in empirical investigation. All these steps require an understanding of the theoretical framework on which they are based and concepts on the nature of the entities under consideration. While many of the entities required are relatively easy to measure the problem in this group of approaches seems to be in the theoretical manifestation of what the entity means.

The process-based approaches

The second group of approaches identified is referred to herein as the 'process view'. While in the first group of approaches structures are considered spatio-temporal manifestations of processes that occur in various scale domains (Turner et al. 1989, Wiens 1989, Levin 1992, Forman 1995, McGarigal and Marks 1995) other approaches make the processes explicit, quantify, classify them and model them (see e.g. Agarwal et al. 2004). The main methods include geostatistical models, neutral models and processes explicit models (EM) (Turner and Gardner, 1991, With and King 1997, Saura and Martinez-Millan, 2000). EM are explanatory models and are possibly used on other regions (and sometimes other scales) submitted to the same processes. The models, we are talking about, are numerical simulations able to produce complete dynamical landscape evolutions, i.e. composition (number and proportion of land covers) and configuration (spatial arrangement of these land covers) landscape evolutions. Such models may be differentiated from Geographical Information Systems (GIS) or remote sensing Land Use and land Cover Change (LUCC) models sometimes called landscape models (Müller and Steinhardt 2003, Agarwal et al. 2004).

These processes include fluxes of substances, matter and energy, as well as interactions among organisms. Pattern and related processes are encapsulated in a cause-and-consequence relation, which is non-linear and, to a certain degree, bi-directional. In other words, the observable pattern is often a product of spatially constrained processes (e.g. a groundwater influenced bog area); and vice versa do prevailing structures influence processes (for instance, a new road may be a barrier for former animal dispersal routes).

The energy and matter used or consumed by plants, such as light, water, and nutrients, define resource gradients. Functional gradients describe the response of the biota to indirect, direct, and resource gradient types (Müller 1998). Included in this gradient category would be biomass and leaf area index (Müller 1998). Rollins et al. (2004) succinctly summarize the main strengths of such an approach. Regarding the fourth dimension of landscape we only highlight that a combination of remote sensing, ecosystem simulation, and gradient modeling allows to create predictive landscape models and for the use of indirect, direct, resource, and functional gradient analysis for mapping different dominating regimes or overarching processes.

The natural capital paradigm suggests that it is not so much the landscape patches or basic entities themselves that are important, as the natural functions they support or sustain, and ultimately the goods and services they provide for people. According to Potschin and Haines-Young (2006), a sustainable landscape is one which is able to maintain the outputs of ecosystem goods and services that people value or need, and that the key research focus for Landscape Ecology is to understand the biophysical, social and economic boundaries of the space in which this is possible. In the newer literature, more authors argue that Landscape Ecology should move away from the mere description of spatial pattern at one, fairly arbitrary point in time, and develop a better understanding of the dynamics of landscape elements. For instance, Käykhö and Skånes (2006) suggest, that this can be done through 'Landscape Change Trajectory Analysis', which seeks to describe in a systematic way, how landscapes change and how 'history' is embedded in the structures we see at any one point in time.

We may utilize the fragmentation process as an example. Epistemologically, the word refers to a process but it is usually expressed through the changes in pattern between two or more points in time. Instead of venturing into the details of fragmentation the reader should refer to (Bogaert 2003, Riitters et al. 2002, 2004). It is commonly agreed that landscape fragmentation mainly results from the conversions and development of sites into urban or other intensively used areas, and from the linkage of these sites via linear infrastructure, such as roads and railroads (Moser et al. 2007). These processes create more or less isolated habitat patches, ecosystems or other land-use types embedded in a matrix of development, that in turn affect ecological interactions (i.e., ecological flows) among habitat patches with severe consequences (Saunders et al. 1991; Forman 1995).

We may conclude that for the analysis, description, quantification and classification of structures for given temporal snapshots a wide range of tools and methods is available although problems with multi-scale analyses remain. For instance, Riitters et al. (2004) point out that multiple-scale protocols are needed for landscape assessments, not because the answer changes with observation scale, but rather because different answers potentially are all relevant in different ecological circumstances (Wiens 1989, Levin 1992). There is an increasing awareness of the diverse theoretical and methodological approaches which have underlain the study of landscape ecology and which need to be reconciled for the explicit study of the fourth dimension.

James Wickham opened the stage with an overview presentation and a critique of patch-based landscape indicators for detection of temporal change in fragmentation (Wickham et al. 2007). Especially for landscape change detection metrics are often difficult to interpret and can sometimes lead to counterintuitive results. Typically, one needs to fix the observation scale.

The two following presentations from researchers from Ghent University, Belgium, underpinned and further examined these findings. For the province of Flanders Verle van Eetvelde demonstrated the applicability of quantitative techniques for assessing spatio-temporal patterns of landscape changes. Ilke Werbrouck further analyzed historical maps and integrated them with recent LiDAR elevation data for a landscape reconstruction approach. These two interlinked presentations provided at least partially solutions to the many questions and problems brought up by James Wickham and pointed out that GIS and - increasingly - Spatial Data Infrastructures may be able to serve as backbones for landscape research when integrating different spatial and temporal resolutions.

Scale in landscape analysis

As heterogeneity depends upon the scale, landscape pattern analysis is strongly influenced by scale (Li and Wu 2007). The analysis can be done at specific and even multiple scales, yet problems exist in defining the relevant scale(s). Conceptual problems like the modifiable area unit problem (MAUP) have a distinct influence on the outcome of landscape structural analyses and require a thorough selection of appropriate metrics and levels of analysis scale. MAUP (Openshaw and Taylor 1979) arises from the fact that selection of spatial units for analysis is often arbitrary. These units can be aggregated into areas of different forms and spatial arrangements which may not correspond to meaningful entities. While MAUP affects the results of statistical analyses, it also “carries critical information we need to understand the structure, function and dynamics of the complex systems in real world” (Jelinski and Wu 1996).

Scale is an important issue in both discrete and continuous models for quantification of landscape structure. The patch-mosaic model has often been criticized for inability of dealing with MAUP (see Kent 2007 for a review) and thematic resolution adds to the subjectivity inherent to the delineation of analysis units (Castilla et al. 2009; McGarigal et al. 2009). Also, surface metrics are highly dependent on the window size, hence on scale and understanding their scaling behavior remains a priority for further research (McGarigal et al. 2009). Recently, Morgan and Gergel (2010) proposed an interesting continuous/discrete model to account for homogeneity over multiple spatial scales using object-based analysis. This model takes into account both “within-object heterogeneity (sub-object variability), and homogeneity over broad spatial areas (dissimilarity to super-object)". Thus, local spatial variability is smoothed into discrete representation as pattern of objects at various scales. However, these objects are still conceptually continuous: they would segment the variable of interest into homogeneous areas whose values are dome by mean values of component pixels. Therefore, subjectivity through labeling of classes is avoided. One challenge to this model is choosing the adequate scale parameters in segmentation so that the resulting segments have meaningful correspondents within the landscape. A recent tool- Estimation of Scale Parameter (ESP) (Drăguţ et al. 2010)- enables meaningful multi-scale pattern analysis with the help of Local Variance graphs (Woodcock C.E. and Strahler 1987).

The invited lecture of Danielle Marceau titled 'Scale issues in Landscape Ecology research: A synthesis' set up the framework of this section through a thorough overview on scale issues in Landscape Ecology. Danielle Marceau emphasized scale and scaling as key research topics in Landscape Ecology (Wu and Hobbs 2007). Moreover, scale issues transcend a particular field, rising as object of a new science - the science of scale - that encompasses three main issues: understanding the impact of scale, determining appropriate scales, and scaling up or down.

Rocco Scolozzi presented a research in collaboration with Davide Geneletti - 'A method to assess landscape functional connectivity at local scale for target species'. This case study in an Alpine valley floor represents a contribution to the assessment of ecological consequences of land-use changes. The functional connectivity is based on the barrier effect as a function of species-specific sensitivity.

Emilio Díaz-Varela presented the results achieved together with his colleagues Pedro Álvarez-Álvarez and Manuel Marey-Pérez. The lecture- 'Influence of landscape pattern on scale divergence in categorical maps'- addressed the issue of identifying characteristic scales in heterogeneous landscape. The novelty of this work consists in calculating Shannon-Wiener index (a measure of spatial organization) within moving windows of different sizes (which simulate constantly increasing scale levels) to detect characteristic scales.

Chun-Yen Chang and Yi-Ting Chang presented the poster entitled 'A cross-scale approach to the biodiversity of birds and butterflies in landscape structure in Taiwan'. The study discusses the relationships between the biodiversity and landscape structures as seen 'through the eyes' of particular species.

Conclusions

The lectures as well as discussions within the symposium emphasized some technical and conceptual problems related to landscape metrics applications, such as: the need to add topographic information; appropriate consideration of scales; and, ambiguity and even contradiction between landscape metrics. The latter prompts for the need to carefully select the most useful metrics for a given application.

Alternative representations of landscapes and related metrics are necessary. However, it is still not clear whether these alternative models should just supplement the patch-mosaic model (McGarigal et al. 2009), or they should replace this model. Some recent research (Price et al. 2009) suggests that both continuous and discrete models may provide good results in particular situations, with no single model being dominant. Two examples of alternative applications have been presented in the symposium: the graph theory and continuous representations (gradients).

Landscape metrics techniques are useful for the analysis of landscape change, but the set of metrics should be reduced to meaningful and fundamental indices (e.g. amount, context and edge measures).

It has been revealed that despite the limitations, the research on landscape metrics is still a vivid field in landscape ecology. This has been proved within the symposium by presentations ranging from tool development, through examples of applications, to conceptual models.

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