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PERSPECTIVE

How has the state-of-the-art for quantification of landscape pattern advanced in the twenty-first century?

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Abstract
Context Landscape ecology was founded on the idea that there is a reciprocal relationship between spatial pattern and ecological processes. I provide a retrospective look at how the state-of-the-art of landscape pattern analysis has changed since 1998.
Objectives My objective is to show how pattern analysis techniques have evolved and identify some of the key lessons learned.
Results The state-of-the-art in 1998 was derived from information theory, fractal geometry, percolation theory, hierarchy theory and graph theory, relying heavily on the island-patch conceptual model using categorical maps, although point-data analysis methods were actively being explored. We have gradually winnowed down the list of fundamental components of spatial pattern, and have clarified the appropriate and inappropriate use of landscape metrics for research and application. We have learned to let the objectives choose the metric, guided by the scale and nature of the ecological process of interest. The use of alternatives to the binary patch model (such as gradient analysis) shows great promise to advance landscape ecological knowledge.
Conclusions The patch paradigm is often of limited usefulness, and other ways to represent the pattern of landscape properties may reveal deeper insights. The field continues to advance as illustrated by papers in this special issue.

Keywords Spatial pattern · Metrics · Indices · Landscape ecology · Scale · Spatial heterogeneity

Introduction

Landscape ecology was founded on the premise that there is a reciprocal relationship between spatial pattern and ecological processes such as the spread of disturbance and fluxes of organisms, material and energy (Turner 2005). Its focus on pattern, process, change and scale sets landscape ecology apart from other branches of ecology (Turner 1989). A binary conceptual model of landscape elements (patch vs. matrix) inspired by island biogeography dominated early attempts to quantify spatial pattern. The conceptualization of landscapes as shifting mosaics (Bormann and Likens 1979) was inspired by the change component of landscape ecology, but consistent methods to quantify the temporal component lagged behind methods to quantify the spatial component.

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In 1998, I published a widely-cited review of the state-of-the-art of quantifying landscape pattern at that time (Gustafson 1998). Attempts to quantify landscape spatial pattern had just begun in the mid-1980s (Gardner et al. 1987; Krummel et al. 1987; Turner 1990), initially borrowing heavily from information theory (O'Neill et al. 1988), but quickly developing new approaches targeted to the unique challenges of large spatial grids and vector maps. By 1998 the landscape metrics field had mushroomed, catalyzed at least partially by the release of FRAGSTATS in 1995 (McGarigal and Marks 1995), software that automated the computation of a large number of landscape metrics. Although the innovation of methods to quantify the spatial pattern of landscapes has shifted somewhat from conceptual methods to technical methods (e.g., remote sensing advances, development of R packages) since the 1990s, there have nevertheless been many significant advances in both our understanding of the fundamental characteristics of spatial pattern and methods to quantify those characteristics.

The purpose of this essay is to provide a perspective on the current state-of-the-art of landscape pattern analysis via a retrospective look at how the state-of-the-art has changed over the last 20 years. My objective is not to produce a comprehensive review of the current state-of-the-art, because that has been done elsewhere (e.g., Kupfer 2012; Lausch et al. 2015; Frazier and Kedron 2017). Instead, my objective is to show how we got to where we are and identify some of the key lessons that we landscape ecologists have collectively learned along the way.

Retrospective

Thirty years ago, the field of landscape pattern quantification was in its infancy. Some of the earliest conceptual developments remain widely used and highly useful today, while others have disappeared almost completely despite considerable promise. Many of today's recent advances had not yet been conceived (or were effectively hidden within other disciplines) even 20 years ago. Here is a bullet list, in the approximate order of their appearance in the literature, of some of the approaches to quantify spatial pattern in use in 1998 and their fate over the last 20 years.

- Information theory provided a framework for some of the earliest attempts to quantify the spatial pattern of landscapes represented as a spatial grid. This approach was pioneered by a group at the Oak Ridge National Laboratory in Tennessee, resulting in the seminal paper published by O'Neill et al. (1988) in the first volume of the journal *Landscape Ecology*. Their work adopted Shannon's (Shannon and Weaver 1949) and Simpson's (Simpson 1949) diversity indices to characterize landscapes, using edge counts to create the still popular contagion index, later improved by Li and Reynolds (1993) and Riitters et al. (1996). This approach inspired other similarly computed metrics to capture other aspects of pattern, such as the interspersion and juxtaposition index of McGarigal and Marks (1995), patch cohesion (Schumaker 1996) and the aggregation index of He et al. (2000).
- Percolation theory was cleverly imported from the physics literature by Gardner et al. (1987) as a way to study landscape connectivity, and it was all the rage in the 1990s. Although percolation theory is rarely directly cited anymore [but see Albanese and Haukos (2017)], its main tenet, that the probability of randomly occupied cells being connected completely across a spatial grid abruptly approaches 1.0 at a predictable fraction of occupancy, is widely known and accepted as conventional wisdom in landscape ecology. Percolation theory also inspired the use of neutral model landscapes (having a pattern generated by a random process) for comparison with landscapes structured by one or more known or unknown processes, to help understand how ecological process creates pattern (O'Neill et al. 1992; With and King 1997). Bob Gardner developed software (RULE and its successor, QRULE) to generate such neutral models of landscape structure (Gardner 1999; Gardner and Urban 2007), which is still commonly used today for a wide range of landscape studies (e.g., Kashian et al. 2017; Shirk et al. 2018). Statistically robust techniques to detect differences in pattern metrics between two landscapes (since probability distributions of metrics cannot be estimated for individual landscapes) have been developed using randomization and simulation procedures (Fortin et al. 2003; Remmel and Fortin 2013).

- Fractal geometry was also imported to ecology from the physical sciences (Burrough 1981; Shelberg et al. 1982; Loehle 1983), and it is a powerful and flexible tool to make multi-scale measurements. Krummel et al. (1987) was the first to use it to describe landscape spatial patterns as found in digital land cover data. Milne (1988) identified five ways to conduct a fractal analysis of landscapes, but only the perimeter-area method caught on, perhaps to the detriment of the field. The perimeter-area measure of fractal dimension was widely used as a metric of patch shape or pattern complexity, but because shape complexity is usually not ecologically important, fractal dimension is rarely reported as a landscape metric these days. One wonders what may have been learned if other fractal measures such as the distribution of mass on a plane [e.g., density of resources or individuals on a landscape, sensu Milne (1992)] or scale-independent fractal measures of diversity were easily computed by metric software in 1998.
- Hierarchy theory was first applied in landscape ecology as a way to help understand the development and organization of landscape pattern (O'Neill et al. 1986; Urban et al. 1987). Although it has subsequently been applied to a wide range of landscape ecological phenomena, it remains widely used as a framework for scaling and understanding the relationship between spatial pattern and ecological process. The substantial power of hierarchy theory to help solve complex landscape problems such as identifying how close a landscape is to a tipping point by analysis of higher-level constraints and lower-level limitations (O'Neill 1989) is perhaps under-appreciated by landscape ecologists today.
- Lacunarity analysis (Plotnick et al. 1993) is a multi-scaled method of determining the texture associated with patterns of spatial arrangements of habitat types or species locations, and it also was all the rage in 1998 (e.g., With and King 1999; McIntyre and Wiens 2000). One of its strengths is that it integrates multiple aspects of spatial pattern such as proportion of the class of interest, contagion, presence of self-similarity and hierarchical structure. Although lacunarity analysis is rarely conducted anymore, it was an informative component in the exploration of multi-scaled approaches to quantifying landscape pattern.
- The recognition that many statistical methods used in ecology are hampered by autocorrelated data prompted the application of alternative approaches adopted from geosciences to performing statistical tests on the autocorrelated data associated with landscape structure (Legendre and Fortin 1989). These methods can use point or mapped data to generate correlograms and semivariograms to quantify autocorrelation within a landscape (Burrough 1995). In the 1990s a great deal of research focused on refining these techniques and learning how to interpret their output to improve the understanding of the link between spatial pattern and ecological process (e.g., Li and Reynolds 1995). Although active research in the development of these techniques has slowed, they still form a critical component of the toolbox of analytical tools (e.g., Moran's I) used by landscape ecologists.
- In 1997, graph theory was imported from the discipline of operations research and was being explored as an alternative lattice structure to represent landscapes (Keitt et al. 1997), specifically as a way to study landscape connectivity (Urban and Keitt 2001). This approach was gradually hailed as a promising way to tackle a number of conservation problems at landscape scales, and although it remains in common use today, it has not become a standard approach, being primarily used to study wildlife habitat connectivity.
- Although not a metric per se, scaling issues in the quantification of landscape pattern were, and continue to be, a fundamental problem that has proven very resistant to persistent attempts to resolve. John Wiens formally put the scaling issue on the table for landscape ecologists in his seminal paper (Wiens 1989), which catalyzed a search for scale domains in pattern metrics (e.g., O'Neill et al. 1996; Wu et al. 2002; Wu 2004). Fractal theory offered great promise to inform scaling methods, but it proved insufficient. It was widely hoped that a "silver-bullet" power-law would be discovered (e.g., Johnson et al. 1992; Levin 1992), but this has not been realized. Scale remains an important research focus in landscape ecology, with new approaches being investigated, such as one that looks at the scaling of pattern in geographic space, as opposed to the scaling of

pattern in pattern metric space (Zurlini et al. 2007). However, although the importance of hierarchies of scale is widely recognized, McGarigal et al. (2016) found that a large majority of published habitat ecology papers do not address multiple spatial or temporal scales.

- A phenomenon derisively called "metric fishing expeditions" using FRAGSTATS was a rampant problem in 1998. Researchers with data on some ecological process on a landscape would compute a large number of landscape metrics for the landscape, look for correlations between the process and each metric and then assume that such correlations indicated some sort of causal relationship. However, because reviewers often called out this behavior by insisting on a test of an a priori hypothesis of a specific mechanism behind such causal relationships, this practice has diminished greatly (but not completely) in recent years.
- Similarly, angst was developing about how to interpret landscape indices and relate them to ecological processes (Li and Wu 2004). Researchers were commonly criticized for quantifying the wrong component of pattern or using confounded metrics, or worse yet, measuring pattern at a scale inconsistent with the process being studied. It was hoped that a metric could be found that captured all relevant aspects of spatial pattern in a single value (Scheiner 1992). A fair amount of research was conducted to better understand the behavior of indices and to find ways to compute independent indices of specific components of landscape pattern (e.g., Gustafson and Parker 1992; Li and Reynolds 1995; McGarigal and McComb 1995; Riitters et al. 1995; Trzcinski et al. 1999). This research was extremely helpful in dispelling much of the pattern metric conceptual fog that was prevalent in 1998, greatly improving our ability to choose appropriate metrics and interpret their values. However, some fog remains, and so we are still adding to our understanding today (e.g., papers in this issue).

I concluded my 1998 review by highlighting the pervasiveness of the island paradigm in studies of spatial pattern at that time, and pointed out that with the exception of edge and adjacency measures, virtually all indices calculated for categorical maps were based on a binary patch model. However, at that time, the discomfort with the patch model as a way to describe the spatial configuration of a landscape was gaining momentum. This catalyzed pioneering efforts to develop other frameworks to study and analyze spatial heterogeneity and its ecological effects. The use of resistance or least-cost surfaces to predict animal movement across landscapes was being pioneered as an alternative to the binary habitat conceptual approach in which non-habitat was considered to be a homogeneous matrix (Knaapen et al. 1992; Gustafson and Gardner 1996; McRae et al. 2008). Today, these techniques have become very sophisticated, often using agent-based models, and are often applied in conservation planning (e.g., Compton et al. 2007; McLane et al. 2011; Pauli et al. 2013). Gradient analysis as an alternative to patch analysis was being investigated for landscape ecology purposes by 1998. One approach used fuzzy logic as an alternative rule to delineate patches, where percent membership in a class as defined by multiple continuous environmental gradients produced a more continuous representation of patchiness (Arnot et al. 2004), but his approach did not take hold. Another approach conceptualizes landscape heterogeneity as continuously varying multi-dimensional gradients resembling a surface rather than abrupt discontinuities, avoiding the substantial loss of information and error propagation that comes with collapsing landscape-level environmental variability into categorical maps (McGarigal and Cushman 2005). Gradient analysis can compute metrics analogous to patch metrics from surface topography, and continuous data are especially amenable to techniques such as fractal and lacunarity and wavelet analysis (Cushman et al. 2010). As an example, Evans and Cushman (2009) used an explicitly niche-based and individualistic approach to predict species occupancy of multiple tree species as a continuous landscape variable, as an alternative to traditional classified community-type vegetation maps. In order to produce general, multipurpose assessments of landscape pattern, Kurt Riitters and colleagues developed an approach that trades precision (focused on a particular process or species) for generality (applicable to many processes or species) (Riitters et al. 2002; Riitters 2005). A fundamental aspect of pattern (amount or density) is measured in a way that lets any user (or species) choose their own scale (window size) and threshold (tolerance of fragmentation) and consult a look-up table to see how fragmented the landscape is for that definition of fragmentation. This approach represents a formal trade-off among generality, realism and precision (Levins 1966), and has proven useful for general, continental-scale assessments of landscape pattern (e.g., USDA Forest Service 2016).

The linkage of landscape pattern and ecological process is being widely studied in terms of landscape connectivity and the movement of organisms. The initial focus on physical connectivity of habitat is gradually being replaced by a focus on functional connectivity that is organism-centered (Kindlmann and Burel 2008; Vogt et al. 2009). The emerging field of landscape genetics similarly describes landscapes in terms of their effect on the spatial distribution and movement of genes and populations rather than focusing on individual organisms. For example, (Peterman et al. in review) have applied a resistance surface optimization approach for this purpose. Cushman (2016) has recently proposed a configurational entropy metric to describe the departure from randomness of a landscape mosaic, enabling a connection to laws of thermodynamics to help understand changes in landscape pattern. It remains to be seen how this concept will be embraced by landscape ecologists, but Gao and Li (in review) provide one perspective, and Nowosad and Stepinski (in review) used an entropy approach to measure landscape complexity. We are also seeing an adoption of landscape ecological principles to study the spatial distribution of human social characteristics (Brown and Reed 2012; De Vreese et al. 2016). Similarly, study of pattern and process in urban landscapes has required the development of 3-dimensional metrics to account for the varying heights found in built environments (Kedron et al. in review). Such metrics may prove useful to describe other ecological phenomena for which volume has meaning, such as niche area in topographical space or shifting habitats in mountainous areas. Given these nascent novel approaches, I fully expect the next 20 years to produce more revolutionary advances to improve our ability to quantitatively link spatial pattern to ecological process.

Lessons learned

If I were to succinctly summarize the lessons learned about quantifying landscape pattern over the last 30 years, several items would rise to the top of the list.

- After decades of debating whether a single, large habitat patch is better than several, small patches, it is becoming apparent that the amount of habitat matters more than its configuration (Fahrig 2013, 2017). We have invested a lot of energy over the last 30 years to identify the fundamental components of pattern, and the list of components has been slowly shrinking. In the early 1990s it seemed the list was endless, but by 1998 we had the list narrowed down to < 10 (Li and Reynolds 1994; Riitters et al. 1995). We then learned that even those components are often confounded in some way (Trzcinski et al. 1999; Baldwin et al. 2004). More recent work suggests that the list may be down to three (Cushman et al. 2008). Importantly, we are now concluding that abundance of cover types and their aggregation are probably the two most important things to know about a landscape (Fahrig 2013; Riitters in review), if, for no other reason, than to properly interpret other metrics. In my own PhD research I used neutral model landscapes to study how a number of landscape metrics behaved as proportion of cover type changed, and the effect was often pronounced and rarely linear (Gustafson and Parker 1992).
- Metrics must be carefully interpreted in light of proportional abundance and the scale at which they were calculated (Gustafson and Parker 1992; Riitters et al. 1995; Wu 2004; Šímová and Gdulová 2012). We have clearly learned that there are appropriate and inappropriate uses of landscape metrics (Li and Wu 2004). It is also critical that they be conceptually linked to process or theory, accounting for the scale of that process, and these putative links should be tested.
- The recent and widespread adoption of the open-source, community-based R project for statistical computing (Chambers 2008) for ecological data analysis is perhaps a “game-changing” development that will encourage the sharing, testing and adoption of novel ways to quantify the spatial and temporal patterns of landscapes. Conceptual advances and the development of analytical tools (e.g., FRAGSTATS, GIS, R, Circuitscape) proceed in tandem. Yet, the tools often drive or constrain subsequent conceptual advances (through what metrics are or are not included) such that tools should probably face as rigorous peer review as do journal papers.

- I have personally learned to let the objectives choose the metric, guided by the scale and nature of the ecological process of interest. My own research uses spatial models to project the effect of the processes that structure forest landscapes over long time frames, and I tend to use a small number of simple, somewhat intuitive metrics that are directly relevant to the response variables that are important for a specific study. I guard against being seduced by what can be calculated, being content with what should be calculated (i.e., the most useful/instructive metric(s) for the question at hand).
- Several items on this list suggest that in many cases the traditional patch paradigm may not be the best conceptual framework for landscape analysis. For example, other ways to represent and analyze the heterogeneity and pattern of landscape properties may have much greater utility and reveal deeper insights.
- Some promising approaches appeared in the last 20 years that did not gain any traction, yet may be worth re-visiting. (1) The constraint envelope concept within hierarchy theory (O'Neill et al. 1986) might help advance our ability to predict landscape resilience in the face of global changes. (2) Perhaps it is too late to resurrect interest in the application of fractals as a scaling tool, but it would be interesting to study whether other computations of fractal dimension (Milne 1988, 1992) might be more ecologically useful than the perimeter-area formulation. (3) If we collectively persist in relying heavily on the traditional patch paradigm, perhaps the use of fuzzy logic as an alternative rule to delineate patches (Arnot et al. 2004) can mitigate some of the limitations of the patch approach.

I have attempted to provide an overview of the current state-of-the-art of quantification of landscape spatial pattern through a retrospective of my 1998 review. This overview is by no means a comprehensive review. However, the papers contained in this Special Issue represent some of the best thinking and creative development of new approaches for quantitatively studying and evaluating landscape pattern, and provide a solid, representative picture of the emerging state-of-the-art. It is abundantly clear that the final chapter on landscape pattern analysis has not yet been written.

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