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EDITORIAL

Describing and analyzing landscape patterns: where are we now, and where are we going?

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Introduction

The description and analysis of landscape patterns became a central research issue in landscape ecology with the emergence of the pattern-process hypothesis (Turner and Gardner 1991). The earliest references to landscape pattern metrics or indices in the peer-reviewed literature were in 1987 and 1988 (Fig. 1a). Gardner et al. (1987) compared the number, size, and perimeters of patches across real and simulated landscapes and established the neutral model concept for comparing landscape patterns. Krummel et al. (1987) demonstrated the first multi-scale index—a fractal dimension describing perimeter-area scaling—while Milne (1988) demonstrated an entire class of multi-scale indices based on fractal geometry. O'Neill et al. (1988) introduced the dominance and contagion indices, the latter of which extended the Shannon species diversity index (e.g. Pielou 1975) to describe the diversity of spatial adjacencies on a map. Those and other early methods capitalized on concepts or metrics developed in diverse fields such as information theory, percolation theory, classical ecology, and fractal geometry.

As more aspects of landscape patterns were recognized, the metrics to quantify those aspects proliferated, so that 10 years later, Gustafson (1998) stated that hundreds of measures of landscape pattern had been proposed. Several reviews have examined the burgeoning array of metrics used in landscape ecology, often with a critical eye (Gustafson 1998; Li and Wu 2004; Kupfer 2012; Lausch et al. 2015; Frazier and Kedron 2017). Critics have taken issue with the long list of metrics that have been applied without knowledge of their ecological meaning or their interpretation with respect to pattern per se. These issues have also limited our ability to integrate results from different studies in two ways. First, the concern about the ecological meaning of a metric is usually addressed by increasing the specificity of the metric according to the objectives and scale of a particular study (Gustafson 2019, this issue). Integration with other studies is then complicated by Levins' (1966) classical tradeoff between the precision (specificity)

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and generality of the metric. Second, and a more important concern from a pattern perspective, is that unless the metric can also be interpreted with respect to pattern per se, the effects of pattern cannot be compared to other studies that use different metrics (Bogaert 2003). Successful integration does not require every study to use the same metric, but it does require knowing what the metric measures and how that underlying aspect of pattern is ecologically relevant.

We suggest the array of landscape metrics has co-evolved with improvements to landscape data and computing capacity. Most early methods and metrics for quantifying landscape pattern relied on the conceptual "patch mosaic" landscape model (Forman and Godron 1981; Urban et al. 1987; but see McIntyre and Barrett 1992; and McIntyre and Hobbs 1999 for some notable early exceptions to the patch mosaic concept). The patch mosaic model emerged when most landscape maps were polygon (patch) format—the earliest landscape ecology studies that examined pattern metrics were based on land use polygon maps converted to categorical raster format for analysis (Gardner et al. 1987; Krummel et al. 1987; O'Neill et al. 1988). The typical map analysis software was raster-based (e.g. GRASS [https://grass.osgeo.org/home/history), and the earliest implementations of landscape pattern metrics relied heavily on the patch mosaic model and metrics derived from categorical maps (Baker and Cai 1992; McGarigal and Marks 1995). Over time, supported by advances in remote sensing, GIS, and computation, it became more feasible to analyze large data sets representing more aspects of landscape pattern, and other conceptual approaches such as surface metrics from microscopy and molecular physics, connectivity metrics from circuit theory, and pattern recognition from mathematical morphology have emerged recently as promising frameworks for measuring landscape patterns from those maps (Vogt et al. 2007, 2009; McRae 2008; McGarigal et al. 2009; Cushman and Huettmann 2010; Kedron et al. 2018).

Despite the challenges and critiques of landscape pattern measurement, the use of landscape pattern metrics has continued to increase over time (Fig. 1a, see also Uuemaa et al. 2013). And, not only has the development of landscape metrics been informed by other disciplines, but the development and usage of those metrics also has grown to inform a wide range of research in ecology, geography, and beyond (Fig. 1b). For example, in the urban studies literature, patch metrics have been used to classify cities into different morphologies and to investigate the relationship between spatial patterns of green space and urban heat island effects (Schneider and Woodcock 2008; Li et al. 2013; Kong et al. 2014). The relatively new domain of macrosystems ecology attempts to link patterns and processes from broad scales to fine scales, and thus the ability to measure landscape pattern consistently across scales is critical (Fei et al. 2016; Potter et al. 2016). And, the recent emphasis on "conserving nature's stage" in conservation planning requires pattern descriptions of the geodiversity—the variety of topographic, soil, and other abiotic conditions—in a landscape (Beier and Brost 2010; Hjort et al. 2015; Lawler et al. 2015; Zarnetske et al. 2019).

These domains of interest in ecology and conservation biology exemplify the universal reliance in ecology on the measurement of pattern, heterogeneity, and diversity of conditions across landscapes. The growing popularity of "big data" in ecology from remotely-sensed imagery as well as in situ measurements, crowdsourced data, and historical archives (Elith et al. 2006; Hampton et al. 2013; Pettorelli et al. 2014; Franklin et al. 2017; Morrison et al. 2017) points to a future in which previously intractable amounts of information may be leveraged to measure and understand spatial pattern. Landscape ecologists are well-equipped to think critically about the methods and techniques that are used and will be developed for pattern measurement to address these challenges. An examination of landscape pattern measurement, its usage, and best practices, can thus provide valuable insights and leadership to inform that future.

Goals of the special issue

In this special issue, with the history and future of landscape pattern metrics in mind, we feature a set of perspectives about the measurement of landscape pattern, research articles on emerging pattern metrics and their applications, and a look to new developments in pattern measurement for landscape ecology. We aim to bring attention to integrated pattern-oriented approaches to measuring landscape patterns. In that vein, we have two distinct but related goals—first, to achieve a vibrant discussion of the essential elements

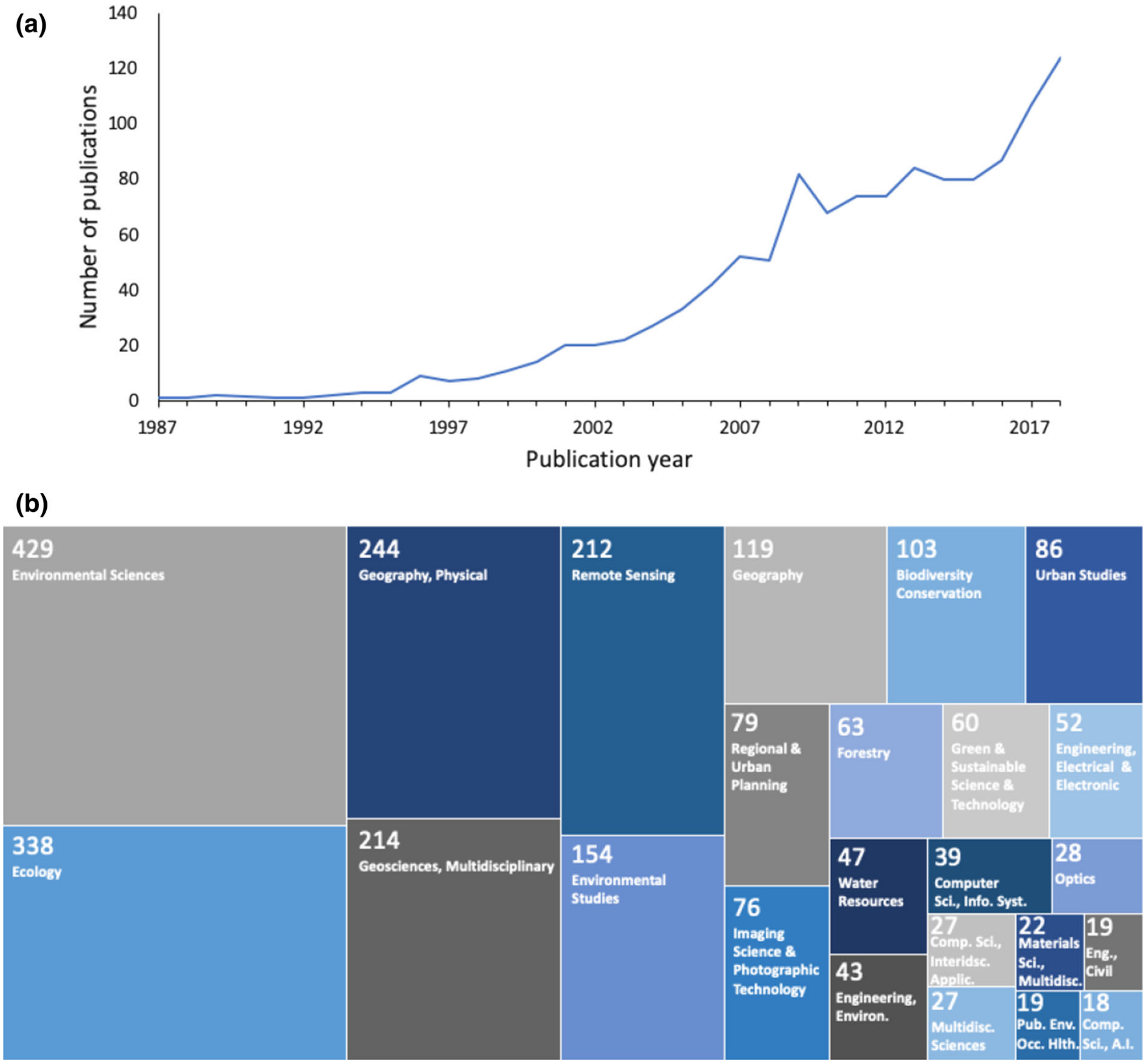

Fig. 1 Number of publications on landscape metrics: **a** over time, annually; and **b** by Web of Science subject category. Web of Science search terms used: "TS = ("landscape pattern" AND metric) OR TS = ("landscape pattern" AND index)". Search included all document types during the period 1900 to present, and 1987 was the 1st year in which publications were found. The 25 subject categories in Web of Science with the most publications meeting the search criteria over the period are shown in (**b**). Publications can be classified into more than one subject category

and descriptors of pattern per se, and second, to provide a venue for "pattern-oriented" ecologists to present new concepts, methods, and applications for measuring and interpreting patterns. Fischer and Lindenmayer (2007) defined a pattern-oriented approach to habitat fragmentation research as one that focuses on correlations between human-perceived landscape patterns and species occurrence. In a transdisciplinary context that is not limited to species' responses to human-perceived patterns, a pattern-oriented approach also considers other pattern-process outcomes (e.g. water quality, fire regimes), land use planning (e.g. landscape context, sense of place), resource management (e.g. conservation, restoration), assessment science (e.g. ecosystem services, environmental security), along with public perceptions (headline indicators) and integration across these perspectives. The contributions in this issue therefore examine a broad range of topics related to measuring pattern that will provide essential information for a wide range of disciplines.

Perspectives on the current state of the field

To help us reach our goal of a discussion of landscape pattern metrics, this special issue features several perspectives on the current state of the field. Gustafson (2019, this issue) reflects on the fate of some of the approaches that were popular at the time of his now-classic review (Gustafson 1998) of the state of the art of pattern metrics. Some approaches, such as the graph theoretic methods that were being developed at the time of that paper (Keitt et al. 1997; Urban and Keitt 2001), are still in wide use today (for example, Saura and Torné 2009), while other approaches such as lacunarity analysis (Plotnick et al. 1993) and fractal geometry (Milne 1992) are rarely used. Frazier (2019, this issue) examines how perspectives from other disciplines can contribute to emerging trajectories and move the field of landscape pattern analysis forward. For example, ideas from the field of regional studies could help broaden the concept of landscape connectivity to include similarity in land management initiatives operating on different sites. Riitters (2019, this issue) suggests that achieving the vision of landscape ecology as a transdisciplinary science (Wu 2013) would be facilitated by revisiting the fundamentals of what to measure and how, if the goal is to characterize landscape patterns per se. Vogt (2019, this issue) points out that pattern analysis—attributing meaning to information—is a fundamental aspect of science. He leverages his experiences developing software for morphological spatial pattern analysis (MSPA) (Soille and Vogt 2009) to note that abstraction and provision are fundamental to pattern analysis as well as software development.

New metrics and models

Several papers in this special issue present new concepts and methods for measurement and analysis of landscape pattern. Nowosad and Stepinski (2019, this issue) derive new information-theoretical metrics that specifically describe landscape complexity. Using simulated landscapes with four land cover classes each, the authors conclude that two pattern metrics—joint entropy, which describes the overall complexity of the landscape, and mutual information, which describes the aggregation of classes—are sufficient to describe landscape patterns. Zhai et al. (2019, this issue) show that transiograms, which are graphs of transition probabilities over a range of spatial lags, offer independent metrics to measure the spatial variability of categorical variables, such as soil types and land cover classes. Kedron et al. (2019, this issue) develop three-dimensional analogues of classical two-dimensional patch-mosaic metrics, and discuss the relevance of those metrics to urban studies using a case study of the built environment in New Orleans. Tarr (2019, this issue) demonstrates a conceptual model specifically for multispecies landscape pattern measurement that combines species-specific requirements to identify hotspots for conservation protection and inform conservation strategies for those locations. Brooks and Lee (2019, this issue) introduce the agglomerative curve (AG-curve) and show that it can be used to distinguish different forms of forest disturbance. In the AG-curve method, a hierarchical clustering algorithm is run on the spatial coordinates of a disturbance or other phenomenon of interest and a curve is drawn to describe the rate at which they agglomerate into successively smaller numbers of clusters.

Novel approaches and applications of pattern metrics

Additional studies in this special issue apply landscape pattern metrics in new ways. Noting that the temporal aspect of landscape pattern has been under-studied, Corry (2019, this issue) shows that annual pattern measurements are necessary to capture pattern changes attributable to conventional agricultural crop rotations. Wickham and Riitters (2019, this issue) study patterns of forest fragmentation using high-resolution satellite data. While they expect to detect ever-smaller canopy gaps, thus increasing measured forest fragmentation, the high-resolution data also detects smaller forest patches, leading to decreased forest fragmentation in some circumstances. Tackling the thorny problem of estimating Boltzmann (thermodynamic) entropy, Gao and Li (2019, this issue) explore the integration of approaches based on the patch-mosaic model (Cushman 2016) and the gradient model (Gao et al. 2017). While they show that the approaches do have some parallel elements, a general method of computing Boltzmann entropy for landscape ecology that integrates the two approaches is still lacking. Peterman et al. (2019, this issue) compare approaches to constructing genetic resistance maps and conclude the best match to true resistance maps was obtained by adaptive optimization incorporating a genetic algorithm.

Ways forward

The contributions to this special issue demonstrate that landscape pattern analysis is an active research field that is producing tools and insights that are critical for landscape ecology and related disciplines. The history and current status of landscape pattern measurement will likely provide hints about its future. Several of the perspectives in this issue point to the future (Frazier 2019, this issue; Gustafson 2019, this issue; Vogt 2019, this issue), as have other recent reviews of pattern metrics (Kupfer 2012; Lausch et al. 2015; Frazier and Kedron 2017). Landscape ecologists have repeatedly borrowed approaches from other fields and continue to do so. It is worth exploring whether there are other methods that could be borrowed, especially given the need for analyzing patterns across non-geographic domains such as soundscapes (Pijanowski et al. 2011).

The future applications of landscape pattern metrics will almost certainly depend on the software and analysis tools available. The software FRAGSTATS (McGarigal and Marks 1995) is often cited as a catalyst for early developments in the field of landscape ecology (Gustafson 2019, this issue). Indeed, Gustafson (2019, this issue) stated that software not only facilitates the adoption of metrics and analysis approaches, but also drives or constrains subsequent conceptual advances. Another example is GuidosToolbox (Vogt and Riitters 2017), which has facilitated the use of MSPA metrics (Schulz and Schröder 2017; Simonson et al. 2018; Vogt 2019, this issue). Freely-available software, TGRAM, is now available to estimate transiograms from maps or imagery (Yu et al. 2019; Zhai et al. 2019, this issue). Conversely, surface metrics (McGarigal et al. 2009; Kedron et al. 2018) are notable new metrics but are not yet widely used, likely in part because they have not been integrated into any software package that is used by ecologists. We note, however, that an R package for calculating surface metrics has been developed recently (Smith et al. 2019, available at https://github.com/bioXgeo/geodiv) and their integration into FRAGSTATS is imminent (http://www.umass.edu/landeco/research/fragstats/documents/fragstats.help.4.pdf). Usability, user-centered design, and specifically the ability of users to visualize pattern metrics and the results of pattern analysis are essential components of software design in landscape ecology (Vogt 2019, this issue).

The perspective in this issue by Frazier (Frazier 2019, this issue) also mentioned that borrowing tools and concepts from the medical sciences and economics to facilitate reproducibility and replication (R & R) would enable transdisciplinarity in landscape pattern analysis. While it may not be possible to fully reproduce many ecological studies, we think that the development and usage of a set of well-defined metrics to analyze landscape pattern can be a critical part of a culture of computational reproducibility across the field of landscape ecology. Computational reproducibility is the ability to produce equivalent outcomes from the same data set using the same software and code (Powers and Hampton 2019). Freely available software, along with pattern metrics that are useful in a wide range of studies certainly contribute to R & R in landscape ecology.

In conclusion, the contributions to this special issue reflect the two parallel developments of landscape pattern metrics that dominate the history of landscape ecology. One has been the search for generality and scaling, including determining the minimum set of metrics with which to measure pattern in any landscape for a wide range of purposes. The other has been developing tailored metrics that could have widespread use for a specific type of analysis. For the same reasons that both up-scaling and down-scaling are complimentary approaches to solving the problem of cross-scale analysis, we believe that both approaches to pattern metric development are valid and useful. By developing and examining the performance and limitations of both general and specific metrics, landscape ecologists have a key role to play in the integration of landscape pattern measurement across many fields in ecology and related disciplines.

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