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EDITORIAL

Advancing a science of scaling in landscape ecology

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Introduction

Landscape ecologists have spent decades examining how changes in the scale of spatial data (e.g., grain and extent) impact spatial patterns that are critical for landscape ecology investigations (Turner et al. 1989; Wu 2004; Saura 2004; Frazier 2016). Yet, beyond the identification and description of consistent relationships, there has been little use of these scaling relationships to predict values at unmeasured scales (Frazier 2014) or uncover generalizable insights into landscape structure and function across ecosystems. In short, our understanding of how measurement scale affects landscape analyses has progressed, but we have limited understanding of what is driving these relationships or how we might build generalizable knowledge about the predictability of data or landscape patterns from these relationships. In fact, in the seminal paper “Key issues and research priorities in landscape ecology: An idiosyncratic synthesis”, Wu and Hobbs (2002) identify *scaling* not scale as a key research priority,

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noting that “general ‘rules of thumb’ and specific techniques for scaling…need to be developed and tested more widely and rigorously.” Yet, nearly 20 years later, we lack a generalizable ‘science of scaling’ in landscape ecology that could contribute to this key priority.

This special issue responds to and renews the call to expand our understanding of scaling in landscape ecology. First, scaling is fundamental to landscape ecology and related fields because landscapes are complex systems characterized by non-linearity, scale dependence, and emergence (Newman et al. 2019). Establishing scaling relationships between measured variables can provide a way to reliably predict those variables at unmeasured scales. Once these relationships are identified, they can be used to track hard-to-predict dynamics and emergent properties of a land system. Second, an observed departure from an established scaling relationship may indicate a possible change in the mechanisms shaping that system. For example, if observed values do not conform to the expectations established by a scaling function, it may signal a change in the scale domain, which could be indicative of a system inflection or other tipping point. Identifying and analyzing such instances is critical to understanding ecosystem dynamics and improving predictions about emergent systems.

Lastly, scaling can help delineate the different forms of clustering that nearly always structure ecological and social-ecological systems. Hierarchically, local environments are nested within larger regional environments, daily behavioral patterns are nested within seasonal variations, and species are nested within a genus. When more than one level of clustering exists, cross structures can also exist that complicate the modeling process. Methodological innovations such as those in multilevel modeling create opportunities to partially pool information across scales, stabilize parameter estimation, and improve our inferences about ecological and socio-ecological processes. When linked with the theoretical framework of hierarchy theory (O’Neill et al. 1986; Urban et al. 1987), these methods have the potential to generate insights about the higher- and lower-level constraints that structure a landscape or ecosystem at a particular scale and lead to innovations in our ability to conduct scaling.

The collection of papers in this special issue advances these concepts and, more generally, a science of scaling in landscape ecology by contributing insights to scaling data, methods, and processes across spatial, temporal, and organizational scales.

Contributions of the special issue

The Special Issue comprises eight papers, including two Perspective articles and one Review. Together, the papers address two central challenges: (1) the need to develop metrics and frameworks for cross-scale comparisons, and (2) the related need to conceptualize and study the multiple dimensions along which scaling can occur. Focusing on foundational concepts like scope, landscape configuration, and entropy through empirical insights from field studies and reviews of conservation programs, the papers collectively set a course for future research. The papers and their contributions are summarized below.

The review article “A review of methods for scaling remotely sensed data for spatial pattern analysis” contributed by Markham et al. (2022) sets the stage for the subsequent empirical papers of the special issue by executing a systematic literature review of the host of methods commonly used when scaling remote sensing-based data for spatial pattern analysis. The authors synthesize their findings in a structured account of the upscaling and downscaling methods available for scaling both categorical and continuous data and discuss the implications of each of these methods for spatial pattern analyses. A useful figure provides practical guidance for researchers selecting among available methods in light of their research problem.

Frazier’s (2022) perspective “Scope and its role in advancing a science of scaling in landscape ecology” focuses our attention on the understudied concept of scope–the ratio of extent to grain–and argues that embracing this concept is key for developing a science of scaling in the discipline. Frazier roots her argument in an illustrative comparison of landscape metric distributions across four scopes. Finding that metric distributions with the same or similar scopes also have similar distributional moments, she posits that scope could be an important organizing device for cross-scale comparisons, replication studies, and the examination of scaling functions. While Frazier’s analysis defines scope spatially, she notes that the concepts extend to the temporal domain, and it would be interesting to investigate whether scope calculations made along other dimensions of scale (e.g., temporal scope) exhibit similar distributional clustering. The hierarchical structure of ecological systems suggests similar patterns could be expected in many systems. Understanding how different dimensions of scope interrelate and correlate to the likelihood of replicating research findings across landscapes could rapidly advance our understanding of ecosystems.

Huckeba et al. (2022) take up the challenge of identifying a measure capable of facilitating the cross-scale analyses needed to test and validate different forms of scaling in their article “Multi-scale spatial ecology analyses: a Kullback information approach”. The authors adopt entropy as their key device and introduce the Kullback Information Index as a scale-independent entropy measure along with a framework for comparing system entropy across hierarchical or organizational levels. In doing so, Huckeba et al. contribute to the growing literature on spatial configuration and entropy in the discipline and make an explicit attempt to connect the insights of that work to the challenge of scaling. Gann and Richards (2022) similarly address measurement issues that rest at the base of examinations of scaling in landscape ecology in their article “scaling of classification systems — effects of class precision on detection accuracy from medium resolution multispectral data”. The authors analyze the scale-dependent nature of land cover class definitions and provide an application of the muti-dimensional grid-point scaling algorithm as one way to address this issue. By improving the accuracy, consistency, and comparability of classifications across scales, the algorithm should better position researchers interested in scaling to differentiate between real scaling relationships and those that are the product of data aggregation issues.

The article “Scaling spatial pattern metrics: impacts of composition and configuration on downscaling accuracy” (Frazier et al. 2021) similarly focuses on landscape composition and configuration, but the authors examine how the composition and configuration of fine-scale landscape information affect the performance of scaling functions created through coarse-graining. Using neutral models to control landscape structure, the authors demonstrate that predictions made with scaling functions are more sensitive to landscape configuration than composition, and that the prediction accuracy of the commonly observed power law scaling functions degrades rapidly as function exponents depart from a certain range. As such, this paper provides suggestive evidence about the types of information loss that may be most important to track during coarse-graining if a researcher wishes to use a related scaling function to study an ecological system. Integrating this work with the scope and entropy frameworks proposed above could provide additional insights into the impacts and reliability of coarse graining.

Safaei et al. (2022) address the common challenge of scaling field-based observations to match remote sensing imagery gathered at different spatial scales in their article “Mapping terrestrial ecosystem health in drylands: comparison of field-based information with remotely sensed data at watershed level”. Motivated by a desire to monitor indicators of ecosystem health linked to United Nations Sustainable Development Goals across large spatial extents, the authors develop a provisional workflow that demonstrates one way of scaling and linking qualitative field-based assessments of ecosystem health with landscape characteristics calculated using publicly available remote sensing imagery. Tested in central Iran, this workflow opens the door to further research refining and elaborating on the proposed approach and testing its generalizability to other environments. Linking to the theme of this special issue, future research could also test the robustness of the authors’ approach to the scaling and integration of data at different spatial and temporal scales. Understanding the spatial, temporal, and environmental horizons at which new approach breakdown is essential to the advancement of landscape ecology and to understanding ecosystem functions.

Adopting a scale dynamics approach, Rittenhouse et al. (2022) examine how an explicit recognition of different types of scale may impact the coordination and success of conservation programs in their Perspective “A scale dynamics approach to integrate landscape conservation within and across jurisdictions”. Analyzing landscape conservation design projects across the eastern United States, the authors demonstrate that focusing only on the location and extent of conservation activities (spatial scale) and the ecological benefits of those activities (ecological scale) hindered coordination across projects and reduced the continuity of conservation activities. These findings offer an interesting potential addendum to the three-part hierarchy of scale first proposed by Wu (2007). While Wu argues that altering the components of scale (e.g., grain, extent) is the hallmark of scaling information about a ecosystem or landscape across spatial, temporal, or organizational levels, Rittenhouse et al. extend these concepts by suggesting the nuanced understanding of the kinds and dimensions of scale may be critical to effectively designing, implementing, and scaling conservation efforts.

This insight is further reinforced by Donovan et al. (2022) in their article "From polyps to pixels: understanding coral reef resilience to local and global change across scales," which uses an illustrative case study of a Hawaiian coral reef to demonstrate how new technological and analytical tools can be used to collect and integrate data collected across both spatial and biological scales. The authors also clearly delineate the scales of measurement, impact, and management affecting coral reef systems worldwide, setting a conceptual framework for future interventions. Ultimately broadening our perspective on scaling to include the study of how information about interventions translates across landscapes, regions, and political units will be an important research frontier as we develop a science of scaling. As several papers in this special issue demonstrate, we have a sound understanding of how many ecological processes work in specific locations over short time horizons. Leveraging that knowledge, we may be able to successfully intervene in those systems in the short run. The scaling question that remains largely unresolved and understudied is where else might those interventions work and for how long.

Concluding remarks and ways forward

As a collection, the papers in this special issue address several barriers to the development of a science of scaling. Markham et al. provide an extensive review of the circumstances under which different scaling techniques should be implemented and offer an easy-to-follow flowchart for selecting an appropriate technique. Using one of these techniques, Frazier et al. demonstrate the sensitivity of landscape metrics to variation in landscape composition and configuration, which has repercussions for how these metrics might be scaled across landscapes. Together, Frazier, Huckeba et al., and Gann and Richards address the challenge of developing metrics and frameworks that facilitate landscape comparisons across scales, and all offer suggestions for ways in which insights might be shared across landscapes. Safaei et al., Rittenhouse et al., and Donovan et al. all provide insight into how to simultaneously analyze data about different dimensions of scale taken at multiple scales with implications for conservation and management.

Applied together, this collection of papers suggests a clear path for future research. As a practical matter, landscape ecologists and researchers in related fields more broadly would benefit from a clearer conceptual differentiation between scale and scaling. The two concepts are, of course, related. However, scaling is not only about how complex systems change with size but also identifying the rules and principles that shape that change. In this sense, the measurement and data aggregation problems addressed by some of the articles in this special issue and more widely in the literature are a step to an ultimate goal of understanding why structured regularities exist. To reach that goal, an important next step is to develop approaches that can identify and understand the processes that are driving the scaling relationships.

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