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PERSPECTIVE

Scope and its role in advancing a science of scaling in landscape ecology

Amy E. Frazier

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Abstract
Context The scope of a measurement is the ratio of the range (or extent) to the resolution. Scope can also be defined as the number of steps in a measurement instrument given the step size or the distance between two points on a space-time diagram. Scope differs from scale in that it is dimensionless and thus provides a means for comparability across studies.
Objectives This perspective argues that advancing a science of scaling in landscape ecology can benefit from acknowledging and embracing the concept of scope to facilitate replications and provide linkages to scaling laws.
Methods Scope is defined and linked to existing focii on scale in landscape ecology. A simple case study demonstrates how landscape metrics computed for several extent-to-grain ratios are more similar according to scope than either grain or extent.
Results Metric distributions naturally group according to scope, with same/similar scopes displaying more similar means and distributions. Distribution shapes also show similarities according to scope, supporting the use of scope for comparisons and replications.
Conclusions Recommendations for moving forward include setting the scope of a study based on the phenomenon under investigation, reporting grain and extent to permit scope calculations, and undertaking comparisons and replications based on scope.

Keywords Grain · Extent · Scale · Scaling · Spatial pattern metrics · Spatial allometry · Power laws

Introduction

Advancing a science of scaling in landscape ecology is a formidable challenge. Scientists have long recognized that local experiments cannot be extrapolated directly to larger scale questions (Carpenter et al. 1995). This is especially true in landscape ecology, where landscapes are patchy and heterogeneous. Experiments conducted at large scales pose difficulties though for hypothesis testing and replication (Hargrove and Pickering 1992; Schneider 2001a). One solution is to advance the science of scaling to permit the prediction and inference of quantities measured at one scale to another. However, identifying these scaling relationships in landscape ecology is no trivial task. Not only do they need to be identified for a particular area or phenomenon, but in order to be universal, they must hold across space and/or time to

A. E. Frazier (✉)
Spatial Analysis Research Center (SPARC) and Center for Global Discovery and Conservation Science, School of Geographical Sciences and Urban Planning, Arizona State University, 85281 Tempe, AZ, USA
e-mail: Amy.Frazier@asu.edu

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provide generalizable insights into landscape functioning across large areas.

Ecologists have engaged in multi-scale analyses for more than a century (Mercer and Hall 1911), resulting in the knowledge that the scale at which an analysis is undertaken impacts results. Landscape ecologists fully embraced this concept with research on the scale-dependency of relationships, processes, and landscape metrics (e.g., Wiens 1989; Turner et al. 1989; Levin 1992; Wu 2004; Wu 2007; Cushman and Landguth 2010; McGarigal et al. 2016, among others). Yet, despite the profusion of scale-related research, landscape ecology lacks a 'Kleiber's Law' to guide investigations. Kleiber's law demonstrates that metabolic rates scale with mass for the vast majority of animals from ants to mice, humans, elephants, and everything in between (Kleiber 1961). This universal scaling relationship has given rise to a multitude of theories and explanations in biology. In landscape ecology, we have observed empirical evidence of scaling for certain landscape components, namely spatial pattern metrics, with studies showing that certain metrics scale predictably as measurement length (resolution) changes (Turner et al. 1989; Wu 2004; Frazier 2014, 2016; Arganaraz and Entraigas 2014, Frazier et al. 2021). Yet, we do not know why these relationships occur and whether they are driven by underlying processes or are simply a manifestation of the fractal nature of landscapes.

In this perspective, I argue that advancing a science of scaling in landscape ecology will benefit from acknowledging and embracing the concept of scope. While scale is the relative size or extent of something, measurement **scope** is a ratio of the range (extent) of a measurement instrument to the resolution. Scope can also be defined as the number of steps in a measurement instrument given the step size or the distance between two points on a space-time diagram (Schneider 2009). The concept of scope is not new to ecology or landscape ecology. Schneider (1998, 2001a,b) championed the importance of scope for applied scaling theory in ecology decades ago, but the concept was never fully embraced by landscape ecologists. The field has instead favored testing multiple scales to determine how results change. Because scope is dimensionless, it provides a means for comparability across studies in a way that multi-scale studies do not, regardless of the data or measurement unit employed. Shifting focus from scale, per se, to scope can help determine the degree of comparability of different experiments, thereby fostering replication and encouraging new insights toward a science of scaling.

In the sections below, I detail the definition of scope and review its history in landscape ecology along with a discussion of how scope can help advance a science of scaling. I then offer a proof of concept of how comparisons across similar scopes are more informative than comparisons across scale. I end by suggesting ways in which we might advance a science of scaling in landscape ecology through scope.

Scope and its importance for comparative replications

The terms 'scope' and 'scale' are often used in tandem, sometimes interchangeably, especially when referring to the scale of measurement, but they are acutely different (Fig. 1a). The term scale has been defined variously in landscape ecology, but here, *scale* of a measurement describes the relative size or extent of something, it has dimension(s), and, by default, units (i.e. 30 m is the scale [resolution] of Landsat imagery). *Scope* is a dimensionless ratio of the upper to lower limits of a phenomena in space or time. It can also be conceptualized as the distance between two points on a space-time diagram (Fig. 1b). In terms familiar to landscape ecologists, scale is the extent (overall area) or grain (size of the individual units) at which a phenomena or landscape is studied, while scope can be considered the ratio of the extent to the grain (Schneider 1998). Extent and grain set the bounds of our ability to detect patterns (Forman and Godron 1986; O'Neill et al. 1996; Turner et al. 1989; Wiens 1989). It is difficult to detect elements smaller than the size of the individual units at which it is measured, and it is impossible to generalize beyond the extent of the study without accepting assumptions of scale-independency (Wiens 1989). Any inferences about scale dependency are thus constrained by those two measures.

While grain and extent are each important on their own, their ratio is even more valuable for extending results into applications of scaling theory (Schneider 1994). From a physical standpoint, the ratio turns dimensional quantities into dimensionless ones so that values can be compared on a relative scale. From a practical standpoint, the extent-to-grain ratio

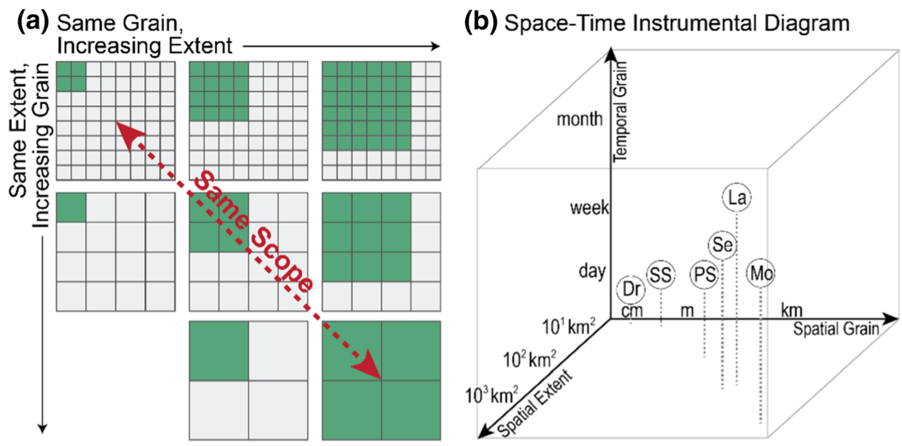

Fig. 1 **a** Grain and extent comparison. Green pixels constitute the landscape, with extent varying along the horizontal and grain varying along the vertical. Landscapes along the diagonal have the same scope. **b** Space-time instrumental scope diagram for common optical remote sensing platforms: Drones, SkySat, PlanetScope, Sentinel, Landsat, MODIS. Spatial extent is plotted as instrument swath width

determines which processes can be reflected in the results (Odgaard 1999). The extent-to-grain ratio, or scope, can therefore provide insights into the robustness of a study. For example, in landscape ecology if the extent-to-grain ratio is too small, boundary effects may dominate, leading to questionable metric computations or truncating patches. Many metrics are quite sensitive to scope, particularly those involving edge/perimeter measures or length-to-area measurements, and so simply reporting scope can provide insight into the applicability of the findings. Lastly, boundary effects increase as the landscape extent decreases relative to the patchiness or heterogeneity of the landscape. Defining this ratio is critically important but often dictated by the scale of the imagery (Cushman and McGarigal 2008).

Scope also provides a key way to facilitate replications and assess the comparability of different experiments. Replications are a central tenet of the scientific method and enable the self-correcting mechanism to prevail. Research is replicable if the same (or very similar) methods can be applied to new data that have been collected and produce the same (or very similar) results (Kedron et al. 2019). Successful replications are needed to bridge scientific theory, which explains why phenomena occur, and scientific laws, which explain what phenomena happen. Difficulties for replication arise for scientists working in geographic space due to the uncertainties introduced by spatial context and spatial relationships (Kedron et al. 2019) as well as the conflicts that arise from needing to study landscape processes at large scales (Hargrove and Pickering 1992). Replication is further complicated by a lack of consistency in the scales at which multi-scale studies are undertaken, which makes the comparisons needed to advance a science of scaling difficult or impossible. Analytical uncertainties that typically accompany the choice of scale for a scientific study are magnified when a replication is attempted at a different scope. Studies undertaken in different geographic areas (and potentially even with different sampling schemes) may be more reliably compared if they operate at the same (or similar) scope. Lastly, comparisons across scope mean that landscapes measured with different extents or grains may be comparable, facilitating meta analyses with published studies.

Case study: comparison of landscape metrics

To demonstrate how comparisons across same or similar scopes can provide improved insights over comparisons across grain or extent, forest cover was sampled from a single ecoregion (EPA 8.1: Mixed Wood Plains) in the northeast and northern Midwest regions of the United States. Within the ecoregion, a random sample of 125, 20 × 20 km (400 km^2) plots were selected (outside urban areas with more than 500,000 people), and the NLCD map was clipped and aggregated to a single 'forest' class following Riitters et al. (2012) to create binary maps of forest-non forest (see Frazier and Kedron 2016 for additional details). Within each 400 km^2 extent, the 30 m land cover data were coarse-grained to 60, 120, 240, and 480 m using majority rules aggregation. Each extent was also scaled by half (0.5) and a quarter (0.25) (i.e. to 100 km^2 and 25 km^2, respectively) using the center point of the original extent. This process of extent scaling is also called 'rating' (Schneider 2009). Overall, three extents and five resolutions were generated from which to examine scaling across five scopes (Fig. 2a). Class-level landscape metrics were computed for all 125 samples at all 13 grain-extent combinations. A range of metric types were tested including aggregation, area, density, edge, and shape metrics that included mean and area-weighted mean statistics. Metric distributions for each combination are visualized through ridgeline plots to facilitate comparison across similar scopes and scales (grain/extent).

Results are presented for three metrics representing three categories: an aggregation metric (NP: number of patches), a shape metric (LSI: landscape shape index), and an area metric (LPI: largest patch index). Ridgelines in each plot (Fig. 2b-d) are ordered from top to bottom according to the mean of the metric distribution. Distributions are colored according to scope (Fig. 2a). Several trends emerge. First, the distributions naturally group according to scope, rather than grain or extent, with same/similar scopes displaying more similar metric means. Second, distribution shapes show similarities within scope groups that do not necessarily translate between scope groups. For example, the results for NP (Fig. 2b) show almost

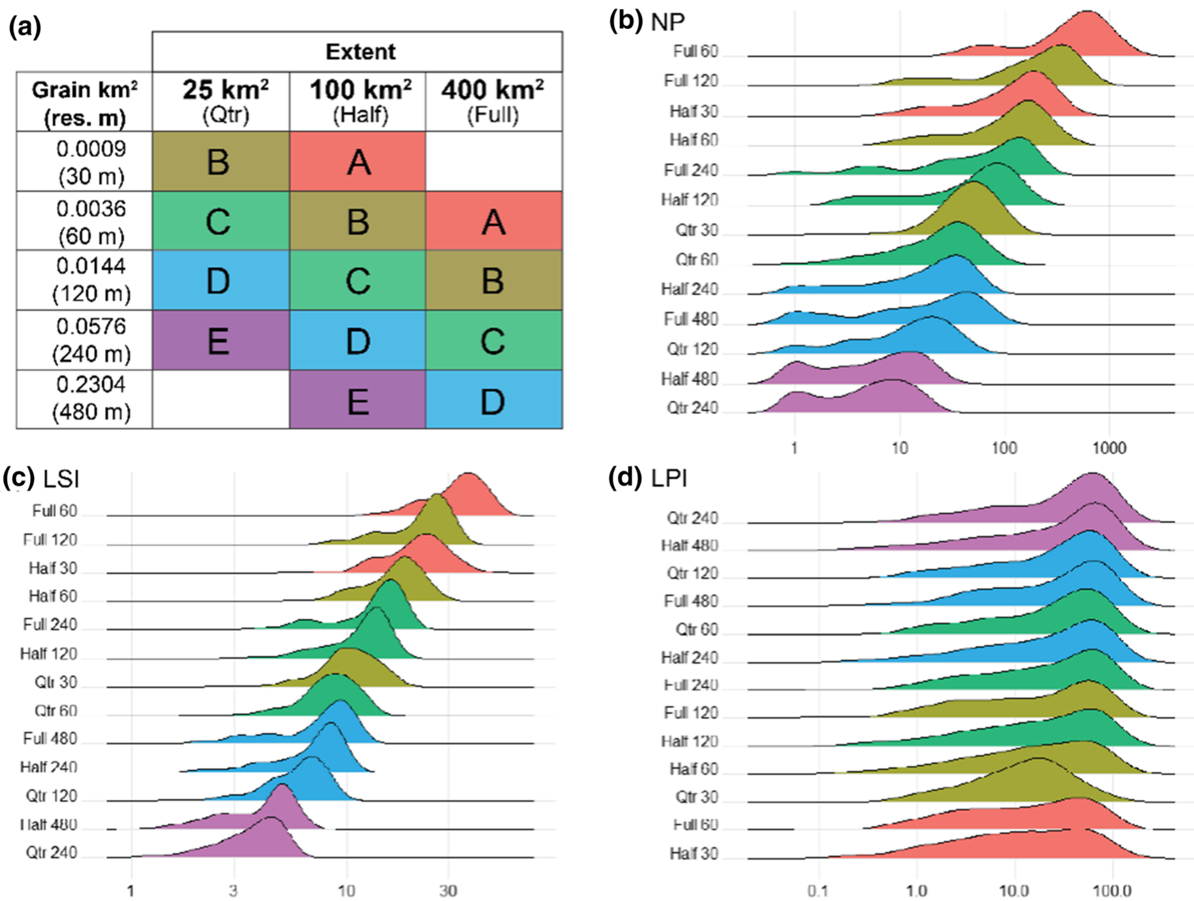

Fig. 2 **a** Scopes for three extents and five grains with letters indicating which extent-grain ratios are equal in scope. The smallest/largest extent was not computed for the largest/smallest grain as there were no comparable scopes. Scope A is 111,111, B is 27,778, C is 6944, D is 1736, and E is 434. Ridgeline plots for **b** number of patches, **c** landscape shape index, **d** largest patch index are colored according to scope. Plot colors match the scope colors in (**a**)

identical bi-modal distributions for scope group 'E' (purple), and very similar distributions but with a less-pronounced bi-mode for scope group 'D' (blue). The distributions shift as scope increases to more pronounced unimodal distributions for groups 'C', 'B', and 'A'. Similar distribution shape trends are evident for LPI (Fig. 2d).

Changing scope did not affect all metrics in the same way. Shifts in mean magnitude were much smaller for LPI than NP, and this difference may be driven by the LPI equation, which represents a percentage normalized by the landscape area. Area-weighted metrics (tested but not shown) similarly presented more variation and less sorting according to scope. Lastly, there was a natural progression in values according to scope (e.g., decreasing means with scope for NP and LSI), suggesting that scope may neatly capture the possible heterogeneity in a landscape according to both grain and extent. This simple case study demonstrates how studies replicated at different grains or extents can produce very similar results if the scope remains the same/similar. Landscapes with very different scopes (i.e. A and E) do not necessarily provide good candidates for replication or comparison because their distributions are not expected to be the same, but landscapes with similar scopes (e.g., A and B) may offer better opportunities for comparison.

Moving forward

Scope presents a practical way to move landscape ecology forward in terms of scaling theory while also providing the opportunity to explore whether experimental findings are replicable and comparable. As landscape ecologists have focused on understanding how landscape values change with grain or extent, we may be missing opportunities to understand how similarities across scope permit enriched inferences. Turning attention to scope may also allow scaling theories utilized in many other fields such as physics, meteorology, and biology to guide and be applied to landscape ecological research. Following are three key steps landscape ecologists can take to move the science of scaling forward through scope.

Set scope based on the phenomenon being studied

Researchers often adopt an experimental scale based on available data (e.g., Landsat scenes at 30 m grain) rather than independently determining the most appropriate scope for the phenomenon being studied. Schneider (1994) notes that measurements should be captured at a resolution at least half of the lower limit of the phenomenon and at an extent at least twice the outer limit of the phenomenon in order to bracket the phenomenon. By considering such guidelines when designing studies, it is possible to ensure that an experiment will capture the phenomenon of interest while also establishing a baseline for replications.

However, it should be noted that scope is sometimes constrained by access to existing data and a lack of resources for acquiring new datasets. In other cases, it may be difficult to sample at twice the outer limit of a phenomenon, particularly if the landscape changes drastically within that range. In these cases, this study supports the idea that comparisons may still be possible among studies with common scopes; it was only when scope changed by several orders of magnitude that distributions became distinctly different (Fig. 2). Therefore, even closely matching the expected limits of the study phenomenon may improve comparisons. Advances in image resolution provided through commercial platforms (e.g., Planet and Maxar) and drones along with advances in super-resolution mapping and image downscaling are providing researchers with greater flexibility to acquire data that match the grain of the lower limit of a phenomenon than has previously been possible.

Report grain and extent to permit scope calculations

At a minimum, studies should report both grain and extent so that scope can be calculated for quantitative comparison with other studies. While this point may seem obvious, many studies report grain quantitatively but report extent in casual or qualitative terms (e.g., "Jackson County" or "approximately 100 sq km"), leaving it to the reader to infer the quantitative extent through a map or figure. Simply reporting both grain and extent quantitatively is an easy way to permit scope calculations and foster comparability across studies and meta-analyses. This point extends to the temporal grain and extent of a study as well. Temporal scope is the ratio of the duration of the study to the temporal resolution of measurements (Schneider 2009). As long-term sampling records become increasingly available (e.g., through LTER and NEON), calculations of temporal scope are yet another way to determine the degree of comparability of different experiments, but these components must be reported as a first step.

Undertake comparisons and replications based on scope

This point raises two critical issues that are needed to advance not only a science of scale but the field of landscape ecology in general. Replications sit at the crux of the scientific method, yet science is in the midst of a replicability crisis in which many fields have discovered published findings may not be replicable. Questions have been raised about the extent to which replication should be possible in geographical studies given the role of spatial context and observation (Kedron et al. 2019), but the answer is not yet known. Researchers in landscape ecology can contribute to overcoming the replicability crisis by attempting replications of prior studies at similar scopes, adding to the body of knowledge on whether we should expect certain experiments to replicate. Replications across *different* scopes may also contribute to advancing theoretical foundations such as hierarchy theory (Allen and Star 1982) to understand how complex landscapes are hierarchically organized.

This perspective focused on a conceptualization of scope natural to landscape ecologists—grain-to-extent ratio—but the definition permits other conceptualizations including the ratio of the largest measurement to the smallest (Schneider 2009). This 'large/small' view translates to power laws (Schneider 1998; 2001a,b; 2009), which relate the scope of one quantity to another through a scaling exponent. Power law scaling in landscape ecology has mainly focused on relating the scope of a quantity (e.g., a landscape metric) to measurement scope (Wu 2004; Arganaraz and Entraigas 2014; Frazier 2014, 2016; Frazier et al. 2021). In this type of fractal scaling, iterative measurements are taken of the same object at successively coarser scales. Moving the science forward will require a more concerted focus on scaling quantities, such as how ecosystem services scale within different forest patch sizes or shapes.

Lastly, the case example explored here focused on raster datasets, but landscape ecologists frequently work with non-raster datasets including polygons and points. Polygons representing sampling plots can be conceptualized in terms of scope by dividing the survey area by the size of an individual polygon. If the 400 km^2 survey areas in the case study were instead sampled using 100×100 m plots, then the scope would be 400 km^2 $\div$ 0.01 km^2 = 40,000. Polygons representing a phenomenon (e.g., patches of bark beetle infestation) can also be quantified as spatial scope by taking the ratio of the largest to smallest cases. A single measurement can also have a scope, which is the ratio of its magnitude to precision (Schneider 2009), and this conceptualization neatly translates to measured points in space. The scope of point data, such as bird counts, can also be viewed via a space-time diagram (see Fig. 1b) in which the spatial grain at which the points were captured is plotted against the temporal grain. Scope then becomes the distance between points on the diagram.

In closing, this perspective argues in favor of a shift toward using and reporting scope in landscape ecology to facilitate comparisons and replications. Schneider (1998, 2001a, b) argued more than two decades ago that scope provides a means to extend scaling theory into ecological investigations and ultimately improve inference. As advancing a science of scale remains part of the research agenda in landscape ecology, scope should be part of the discussions. The linkages between scope and scaling relations, specifically power laws, may in turn lead to identifying a Kleiber's Law of landscape ecology. Next steps should include thoughtful selection and reporting of scope in scientific papers to permit replications by other researchers.

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Data availability Metric data for the case study are available at: github.com/amyfraz/scope.

Code availability code for processing the case study data is available upon request.

Declarations

Conflict of interest Nothing to disclose.

Ethical approval Not Applicable.

Consent to participate Not Applicable.

Consent for publication The author consents to publication.

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