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EDITORIAL

Placing landscape ecology in the global context

Amy E. Frazier

Nearly 40 years ago, the Allerton Park workshop (Forman 2023) defined landscape ecology as a regional science that focused on landscape scales aligning with how humans saw and experienced the world. Since then, advances in high-performance computing and more accessible remote sensing data have facilitated an era of "global-scale mapping" where researchers are now able to swiftly analyze data across large spatial and temporal scales (Foody 2023). The ease with which planetary-scale analyses can now be run is transforming the research thrusts in many fields by providing a macroscope from which to identify biodiversity hotspots, global trends, and other priority areas for conservation on a world scale. Global maps can provide a broader context in which to situate local decisions (Chaplin-Kramer et al. 2022), facilitating their use in setting conservation and land use targets worldwide and prioritizing interventions (Brooks et al. 2006; Cumming 2007). While there are some arguments against their use and development (Wyborn and Evans 2021), global-scale analyses and maps will likely continue being used in prioritization research and by decision and policy makers into the future.

Several recent papers (Guerra et al. 2020; Mendes and Prevedello 2020; Tsavdaridou and Mazaris 2021; Brennan et al. 2022) have elevated landscape ecological investigations to this global stage, extending key concepts such as fragmentation and connectivity to a planetary scale. Yet, a key question that remains is whether global scenarios are prone to disregard fundamental landscape ecology concepts such as pattern-process relationships, spatial and temporal interactions across heterogeneous landscapes, the ecological consequences of heterogeneity, scale dependencies, and hierarchy theory when the landscape perspective becomes occluded at the global scale. As large-scale analyses permeate science and policy, it is an opportune time to examine the circumstances and prospects for landscape ecology in the global realm. This editorial scopes the historical positioning of landscape ecology, from its conception at Allerton Park as an explicitly 'regional' science, to establish a baseline

A. E. Frazier (✉)
Department of Geography, University of California-Santa Barbara, Santa Barbara, CA, USA
e-mail: afrazier@ucsb.edu

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from which to examine landscape ecology in a global context. Next, it addresses how landscape ecology has evolved over the past decades to respond to globalization and global perspectives while also tempering that evolution with a discussion of some of the limitations that global data and analyses pose for landscape-level investigations. The editorial ends by discussing how global perspectives can be balanced within disciplinary foundations to ensure key landscape perspectives remain at the forefront of policy and action worldwide.

The historical scoping of landscape ecology as 'regional'

The interdisciplinary science of landscape ecology evolved uniquely from ecology based on its spatially explicit methods and focus on landscape-level characteristics and issues. Early scholars described landscapes as being in the realm of 10–100 km across (Forman 1995), or colloquially what can be "seen from an airplane window" (Forman 2023), with repeating elements of different land covers or ecosystem characteristics. Landscapes were conceptualized as being nested within broader regions, and this perspective is reflected in the pseudonym "regional ecology" used to define the field following the Allerton Park meeting (Risser et al. 1984). From the start, both the landscapes and regions for investigation reflected the 'human scale' at which people saw and experienced the world (Forman and Godron 1981; Pickett and Cadenasso 1995). This anthropocentric perspective of landscape ecology was characterized by Carl Troll (1939) as "the total spatial and visual entity of human living space." Sampling schemes and study extents were designed according to these landscape scales defined by the clustering of stands or ecosystems (Forman and Godron 1981), and these scales also coincided with scales of human perception, experience, and design being articulated by landscape architects (Nassauer and Opdam 2008). More recently, Wu (2013a) reminds us that "landscapes are the scale at which people and nature mesh and interact most acutely". So, from the outset, landscape ecology was clearly positioned as a regional science, where connections, linkages, and couplings were studied across areas that were large (10–100 kms) but still within the bounds of what the human eye and experience could perceive.

Within this "landscape-scale" extent, studies were also bounded by the resolution, or grain size, at which phenomena could be resolved. Spatial heterogeneity was, and still is, a key concept driving the grain and extent at which phenomena are observed and analyzed, and it has remained a foundational component of the discipline (Pickett and Cadenasso 1995), with pattern, process, scale, and hierarchy closely linked (Wu 2013b). Since spatial heterogeneity and the patterns it produces are inherently scale dependent, landscape ecologists have long recognized the importance of choosing an observation grain appropriate for the intrinsic scale at which a pattern or process is operating. Patches, or homogenous areas that differ from their surroundings, quickly became the foundational building blocks for spatial pattern analyses (McGarigal et al. 2012) in landscape ecology as well as a theoretical cornerstone for the discipline (Risser et al. 1984). The size, shape, and spatial configuration of patches are vitally important for understanding connections, linkages, and flows of energy and materials across landscapes, and landscape ecologists have long understood that the observational grain must be much smaller than the average patch size to permit analysis of these patch components (O'Neill et al. 1996).

While many studies have considered global- and continental-scale influences or framing, notably within a structure of hierarchy theory, it can be argued that landscape ecology was designed to provide a framework from which to study local and regional landscapes, practically bounded in scope by landscape-scale extents and sub-patch grain sizes (Frazier 2022). As concepts and tools have evolved though, it is an opportune time to revisit this historical scoping of landscape ecology as new data and computational resources are shifting research emphases in many fields.

Landscape ecology in an increasingly connected and global world

Our world is now socially connected and globalized in a way it was not four decades ago, and that warrants a reconsideration of the appropriate scope of landscape ecology studies. Systems thought to be separate are now known to be connected through agents

and flows of energy and materials, and human actions in one corner of the planet can drive landscape patterns many thousands of miles away. Landscape ecology has always been cognizant of these larger socioeconomic processes driving landscape dynamics (Zonneveld and Forman 1990; Bürgi et al. 2004), but it can be argued that the discipline has taken an even greater role over the past decade toward integrating social-environmental systems thinking, including the role of institutions (Frazier et al. 2019; Stuhlmacher et al. 2020; Cumming and Epstein 2020), into landscape ecological studies. Embracing these complex systems and interactions at least partially necessitates that more emphasis be placed on the global context in which 'local', 'regional' and 'landscape' analyses are being performed.

Additionally, our collective understanding of the impacts of global processes on regional patterns has also improved over the last several decades. We know now that many of the flows shaping landscapes, such as aeolian circulation, are globally driven and respond to global change (Thomas and Wiggs 2008). Similarly, disturbances that at one time were studied at regional scales, such as wildland fires, are now critically examined under the lens of synoptic climatologies, and projections are updated based on emerging understanding of global dynamics of future droughts (Ryu et al. 2014). Severe storms, floods, and desertification are other examples of how disturbances, once studied at regional scales, are now being linked to large-scale anthropogenic activities and global climate change. Therefore, the importance of framing studies within a global context and understanding the global drivers of regional and local landscape patterns are now widely understood.

However, while a global lens may be increasingly warranted within the discipline, there is an acute difference between lenses and analyses, and there are practical limitations of global-scale analyses in landscape ecology. First, the data used in global-scale analyses can conceal or obscure patches, which are the fundamental building blocks of spatial pattern analyses in landscape ecology (McGarigal et al. 2012) and a critical component for building generalizable theory. Patches represent relatively homogenous areas of the landscape that differ from their surroundings (Frazier 2019), and they are a key focal unit for understanding species dynamics and diversity, nutrient and energy flows, dispersal, movement, and interactions with the surrounding matrix, and other processes. Data used in global-scale analyses often involves coarse units (e.g., 5–10 km pixels are typical), which eliminate many of the discrete patches that capture the intrinsic scale at which landscape processes are operating. Second, global-scale analyses are prone to ignore the local and regional context that constrain or facilitate flows. For example, a global scale analysis of large mammal movement might overlook barriers such as regional border walls or militarized zones that pose real threats to migration. In an era where global analyses are being elevated, and the data and computing resources exist to perform them, it is sensible to reflect on how to best balance fundamental landscape ecological concepts while also responding to global-scale change and drivers.

Balancing fundamental landscape ecological concepts within a global vision

Landscape ecologists must confront the limitations that global data and maps pose while also evolving to ensure we remain at the forefront of policy and action worldwide. Balancing fundamental landscape ecological concepts within a global vision requires scientists to frame their research at multiple scales and understand what resources and knowledge can best be leveraged at each level (Fig. 1). Global scale scoping can provide context to help identify connections, trends, hotspots and priority areas. Landscape-level analyses provide a focal scale for understanding pattern-process relationships, with patches serving as the foundational buildings blocks for theory developments and spatial analysis. Finally, coordinated responses at the local and regional levels translate science into decisions, policy outcomes, and impact. These steps for balancing landscape ecological concepts within a global vision are detailed below.

Situating landscape ecological studies within a global context through hierarchy theory and co-design

The global changes that are occurring within the Anthropocene era demand that studies be framed with recognition of world problems, large-scale connections, and national and international priorities. Landscape ecologists have always worked within hierarchical and multiscale frameworks and understand the

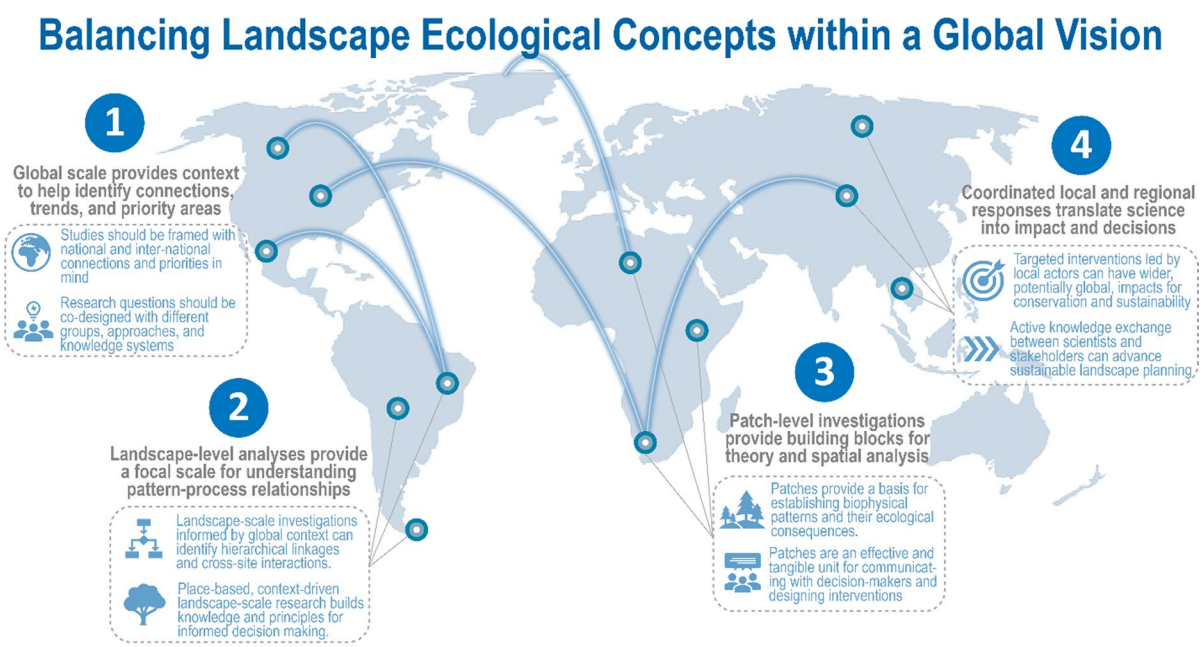

Fig. 1 Landscape ecology concepts and theories can be leveraged at multiple levels within a global vision to frame research, understand relationships, build new foundational knowledge, and contribute to decisions, policy outcomes, and impact

benefits of positioning studies within a larger perspective. Hierarchy theory (Allen and Starr 1982) can provide a useful framing approach for landscape ecology to position studies within the global context while also keeping focus on the regional and landscape scales at which analyses take place. Hierarchy theory is a theory of system organization that recognizes ecosystem processes as being organized hierarchically into discrete scales, or levels, of interaction (O'Neill 2005). Following a basic triadic structure with a defined focal (middle) level, the finer or lower levels contribute the components, mechanisms, and initiating conditions, helping to answer the question 'why', while larger or higher levels contribute context, constraints, control and boundary conditions, helping to explain the 'so what?' (Wu 2013c). Since information obtained across scales has the greatest potential for impact (Chaplin-Kramer et al. 2022), positioning landscape ecology research within a hierarchical framework that responds to the economic, political, and environmental change operating at larger, potentially global, scales while also uncovering drivers at the finer scales where action is possible will be critical for enabling a full understanding of the impacts of those actions.

Practically, global maps and analyses can provide bounded context for identifying connections, trends, hotspots, and priority areas that define the system of investigation. Since maps often serve as a common link for drawing together many diverse voices, landscape ecologists should leverage their close connections with geographers to capitalize on these opportunities. Going deeper, once the investigation area and topic have been determined, research questions that focus on landscape scale processes can be co-designed with different actors and leverage different approaches across a range of disciplinary perspectives so that knowledge is ultimately produced in a manner that can inform management and decisions across scales and borders. Pivotal to this type of co-design approach is situating the process in a particular context, place, or issue (Norstrom et al. 2020) and involving the diverse knowledge systems that exist in those places and contexts (Trisos et al. 2021). Landscape ecology can challenge itself to be more inclusive of other 'ways of knowing' as studies are situated within the global context.

Focusing investigations at the landscape-level to understand pattern-process relationships

Once the questions for research or practice have been defined and situated within the global context, investigations should be targeted at the landscape level to understand pattern-process relationships. Landscapes and regions are a pivotal scale domain not just for landscape ecology but for sustainability science more broadly (Wu 2013a), because it is at these scales where spatial heterogeneity can be investigated and science is actionable. Unlike global systems, landscapes are distinct, measurable units where clusters of ecosystems and disturbance regimes can be parsed and boundaries are relatively distinct (Forman and Godron 1981). Focusing on the landscape level also allows for examining how globalization affects landscape and regional sustainability through landscape sustainability science (Wu 2013a) and where cross-site interactions can be observed, measured, and analyzed.

Landscapes also serve as the key hierarchical linkage between the global and local scales, and maintaining a focus on the pattern-process relationships at landscape scales can help landscape ecologists effectively situate the drivers of landscape structure and the impact of that structure on ecosystem and organism functioning. Focusing on pattern-process relationships at landscape scales fosters an understanding of spatial and socio-economic interactions between humans and the environment and the role of human-caused landscape changes on ecosystem processes. In other words, the landscape is the template on which humans influence spatial patterns and spatial patterns influence ecological processes (Wiens 1999). Perhaps most importantly though, place-based, context driven, landscape-scale approaches can build knowledge and principles for informed decision making as these are the scales where conservation actions are often decided and implemented (Pfund 2010).

Continuing to build foundational theory from the bottom up through patch-based approaches

Patch-based concepts and theories continue to be the cornerstone of landscape ecology and spatial pattern analysis decades after their importance was established at Allerton Park (Risser et al. 1984). While it might be tempting to minimize the importance of patches in favor of more expansive datasets and larger scale analyses, the risk of ignoring 40 years of theory development around ecological mechanisms and systems will have ramifications. For example, using a continuous, global human modification layer as a proxy for organism dispersal and flow without a spatially explicit understanding of where resource patches are located will result in an idealized, but not practical, output for species' movement.

Building from the bottom up with patches does not need to complicate analyses. On the contrary, patches provide a tidy, reductionist approach that render complex objects observable and analyzable, and some of the most impactful theory developments continue to be based on fundamental patch analyses at landscape scales (Haddad et al. 2015; Damschen et al. 2019). A simple and effective framework for studying spatiotemporal dynamics across a range of organizational levels holds that every point in a landscape is either in a patch, a corridor, or the background matrix (Forman 1995). This framework makes it easy to integrate patch-based approaches into analyses and decompose ecological systems as nested, discontinuous hierarchies of patch mosaics (Kotliar and Wiens 1990; Urban et al. 1987). Patches also provide an effective and tangible unit for communicating with other scientists and decision makers, and landscape ecologists should be cautious of approaches and outputs that overlook these key building blocks.

Coordinating local responses to global patterns

Global analyses have been pivotal for uncovering patterns of distant connections and providing the macroscope from which to understand the impacts of policies or actions (Chaplin-Kramer et al. 2022). However, most environmental, landscape planning, and conservation decisions and interventions are made by actors at a range of administrative levels from individual land owners to regional, national, and transnational institutions; but they are rarely made at the global scale (Wyborn and Evans 2021). Recent global analyses of landscape connectivity admit that results should be interpreted in a relative context and paired with local studies to evaluate where to prioritize conservation (Brennan et al. 2022). However, accomplishing this is not a trivial task. A long history of exclusionary practices and 'parachute science' in Western ecology and conservation has

stifled collaborations and coordination of responses with local partners (Trisos et al. 2021). The recent shift toward co-designing knowledge and solutions with diverse actors is a positive step to help integrate essential local knowledge and translate research into action at local scales where interventions can have the most impact. The landscape ecology community can also continue to build an implementation science that centers design in the pattern-process paradigm (Nassauer and Opdam 2008) to help transfer knowledge of landscape patterns and processes into society and create more meaningful responses in policy and practice.

Conclusions

In the decades since the Allerton Park workshop, global-scale disruptions including climate change and the biodiversity crisis have risen to the forefront of research agenda in many fields. Parallel advances in computational power and massive amounts of digital data have prompted an era of global mapping, where researchers can investigate data-driven questions at large scales. For landscape ecology, which has traditionally focused investigations at local-to-regional landscape scales, this shift toward global-scale analyses offers an opportunity to consider how the strengths of the field fit within a global scope. Notably, these strengths encompass a focus on pattern-process relationships at landscape scales that builds foundational theory from patch-based investigations and leverages relationships with a wide range of partners to design solutions to improve the planet. While global analyses do have value, it is important to center the long-standing strengths of landscape ecology while also situating our expertise more explicitly within a global context to respond to the grand challenges impacting the earth. In short, to make global level analyses more actionable, they need to relate to the landscape.

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