[DA-030] GIS&T and Landscape Ecology

Abstract

Landscape ecology is a transdisciplinary science dedicated to the study of the interactions among landscape heterogeneity, humans, and natural system. Since its inception in the mid-20th Century, landscape ecology has been strongly intertwined with spatial technologies, from aerial photography to modern space-borne sensors. Satellite-based remote sensing is among the primary data sources for contemporary landscape ecology analysis, while geographic information systems provide tools to analyze the spatial configurations of satellite derived classifications, simulate landscapes and species distributions, quantify landscape change, and elucidate the reciprocal relationship between spatial patterns and ecological processes. Additionally, global navigation satellite systems, such as GPS, Galileo, and GLONASS, augment these datasets and may be used for data collection to aid landscape ecology research. Emerging geospatial technologies, such as unoccupied aerial systems and micro- and nanosatellites, also have a role to play in landscape ecology.

Keywords: hierarchy, landscape ecology, pattern, process, scale

Author & citation

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Explanation

1. Definitions
2. Introduction and Background
3. GIS&T in Landscape Ecology
4. The Future of GIS&T in Landscape Ecology

1. Definitions

Landscape Ecology: The scientific study of the reciprocal relationship of spatial patterns and ecological processes, the resulting landscape heterogeneity, and changes thereof over time.

Landscape: A heterogenous land area of variable size comprised of interacting ecosystems.

Pattern: The spatial configuration of landscape elements, such as patches, corridors, and mosaics.

Process: Ecological function, such as net primary productivity, energy fluxes, and

biogeochemical cycling, which both influence and are influenced by spatial patterns of landscape elements.

Scale: In ecology, the resolution (dimension) at which ecological processes operate. Often defined based on grain (i.e. minimum resolution of the data) and extent (i.e. size of area under consideration).

2. Introduction and Background

A landscape is a mosaic of varying land use and land cover types, and an interactive expression of environmental gradients and disturbance regimes, both natural and anthropogenic. It is fraught with complexities that transcend spatial and temporal scales. Landscape ecology is a transdisciplinary science that attempts to understand how the heterogeneity in a landscape affects ecological function and biodiversity (Forman and Godron 1986; Turner 2005; Wu and Hobbs 2007). Stated another way, landscape ecology examines the reciprocal relationships between landscape patterns and ecological functions at a variety of spatial and temporal scales (Figure 1). In contrast to traditional approaches to ecology, landscape ecology incorporates both socioeconomic factors and biophysical parameters in the analysis of landscape heterogeneity. Thus, landscape ecology is well positioned to address many contemporary environmental issues, from habitat fragmentation and land use planning to wildlife management and environmental conservation (Hobbs 1997).

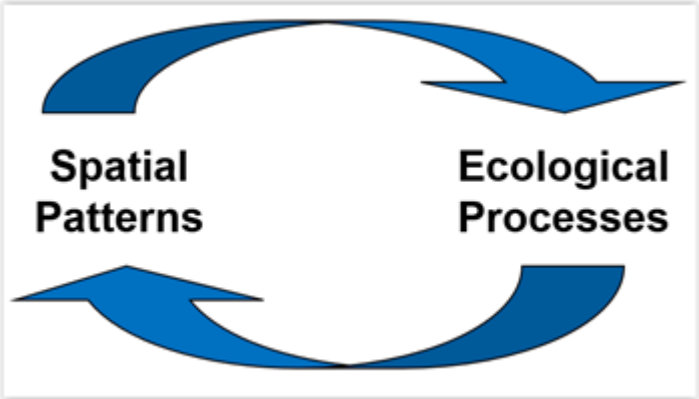


Figure 1. Landscape ecology is predicated on the reciprocal relationship between the spatial patterns and ecological processes across a landscape. Source: authors.

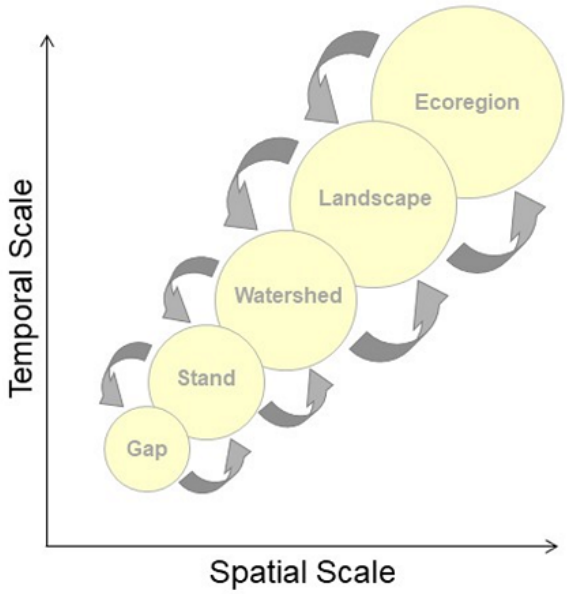
Landscape ecology emerged in Europe in the mid- 20th century when the German biogeographer Carl Troll (1939) applied the term "Landschaftökologie" to describe the study of vegetation/environment interactions using aerial photography. By the early 1980s, practitioners outlined four disciplinary foci for landscape ecology: The development and dynamics of spatial heterogeneity; spatial and temporal fluxes across heterogeneous landscapes; influences of spatial heterogeneity on abiotic and biotic processes; and management of spatial heterogeneity (Risser et al. 1984; Turner 1989). Collectively, these foci have been studied through the lens of scale, landscape structure, and landscape dynamics, emphasizing the effect of spatial patterns on ecological processes (Forman and

Godron 1986; Turner 1989; Forman 1995; Anderson 2008). Subsequently, landscape ecology has drawn from both the biophysical and socioeconomic sciences to explore a range of topics, such as habitat fragmentation and loss (Wu 2013a), ecosystem services in heterogenous and dynamic landscapes (Englund 2017), landscape histories and land use/land cover change (Tappeiner et al. 2021), landscape sustainability and resilience (Wu 2013b; Opdam et al. 2018; Liao 2020), and landscape management (Turner et al. 2002). Additionally, landscape ecology involves innovative techniques to model and analyze landscape patterns (McGarigal 2014).

2.1 Scale

Key to understanding pattern and process is scale (Levin 1992). In ecology, scale refers to the resolution at which ecological observations are recorded. In landscape ecology, investigators consider both the spatial scale (or geographic extent) and temporal scale (or time period under investigation). Broad- or coarse-scale refer to a relatively large area (or time period), while fine-scale refers to a relatively small area (or time period). For example, research that analyzes vegetation dynamics across several states or a region may be referred to as broad-scale, whereas research on the dynamics within an abandoned agricultural field may be referred to as fine-scale. Likewise, a study that consists of daily observations is fine-scaled relative to a study of decadal observations. So, it is crucial in study design for investigators to carefully consider the potential role of scale.

Another tenet is that processes important to ecological function at one spatial scale may not be detectable or important at another. For instance, the processes that affect the distribution of individual trees within a habitat patch (e.g. biotic factors such as competition or abiotic factors like soil nutrient content) may differ from the processes responsible for the distribution of forest types across a landscape (e.g. climatic and geologic factors). There is no single scale that is applicable for all analyses, thus care should be taken to ensure the appropriate scale is selected to address a specific question. Additionally, multiple scales of study may be required to address a question, as is the case when processes operating at one spatial or temporal scale are linked to or affected by processes at other spatial and temporal scales (known as hierarchy within the landscape ecology literature (e.g. Klijn 1994; see Figure 2).



Level	Boundary Definitions	Spatial Scale	Temporal Scale
Gap	Large Tree	0.01-0.1 ha	1s-10s yrs
Stand	Topographic positions; Disturbance patches	1s-10s ha	10s-100s yrs
Watershed	Local Drainage Basins; Topographic Divides	100s-1,000s ha	100s yrs
Landscape	Physiographic provinces; Changes in Land Use or Disturbance Regime	10,000s ha	100s-1,000s yrs
Ecoregion	Climate Geology	100,000s ha	1,000s-10,000 yrs

Figure 2: Both spatial and temporal scales are important in landscape ecology. Processes important at one spatial scale may be unimportant at another scale. Nonetheless, many ecological problems require multiple scales of study and the processes operating at one spatial or temporal scale may be linked to processes at work at other spatial and temporal scale. Image adapted from Urban et al. (1987) and Gergel unpublished lecture slides. Source: authors. Image adapted from Urban et al. (1987) and Gergel unpublished lecture slides.

2.2 Landscape Structure

Prior to the advent of landscape ecology, researchers would often analyze a relatively homogeneous area and results were extrapolated for a larger area under consideration. However, as noted by Monica Turner and colleagues (1995), a founding principle of landscape ecology is that one spatial configuration of a landscape will affect ecological processes in a manner different from another spatial configuration. In other words, landscape ecology is not only interested in how much there is of a particular environmental element (e.g. habitat type), but also the spatial arrangement of those elements. Additionally, landscapes are the product of a suite of biophysical and socioeconomic processes that act upon them. Indeed, another key facet of landscape ecology, which is a distinction from other traditional ecological approaches, is recognition of the role that humans, in conjunction with natural processes, have played in shaping the structure of landscapes.

Landscape ecologists have developed a number of metrics to quantify landscape structure and to relate these spatial patterns to ecological processes (for a complete discussion, see McGarigal et al. 2012 and Frazier 2019). There are two elements fundamental to this framework: 1) the habitat patch, (i.e. a relatively homogenous unit that differ from their surroundings), and 2) landscape mosaics, i.e. a series of patches and corridors (connecting patches) across a landscape (see Forman 1995). Landscape metrics are designed to quantify both landscape composition (e.g. presence, proportions, and variety of landscape classes) and spatial configurations of landscape elements (e,g, spatial arrangements and

distributions of landscape classes) at both the patch and landscape levels. Such metrics are then used to predict ecological processes. For instance, patch area and edge metrics are often related to species diversity and abundance, whereas connectivity metrics may serve as surrogates for dispersal and other ecological flows through a landscape.

2.3 Landscape Dynamics

The dynamics of spatial heterogeneity is another of the key foci of landscape ecologists. A landscape will have compositional and configurational attributes at a specific time. However, these characteristics and associated processes fluctuate with time because of natural variability and anthropogenic agents (Rhemtulla and Mladenoff 2007). For example, land conversion alters the structure of spatial heterogeneity, leading to habitat fragmentation or homogenization, either of which will have important consequences for ecological function and species richness. Similarly, natural disturbance regimes, such as periodic fire or drought can alter landscape structure and function at both spatial and temporal scales that differ from anthropogenic changes, but that nonetheless alter ecological functions. Indeed, research has shown that past events, whether natural or anthropogenic, can have persistent effects on an ecosystem over long periods of time. Therefore, landscape ecologists analyze landscape history and employ simulation models that attempt to predict future patterns. As such, landscape ecology can play an important role in both ecological restoration by determining past landscape histories and conservation through identification susceptible habitats.

3. GIS&T in Landscape Ecology

Given the spatial focus of landscape ecology, GIS&T has played an integral part in advancing the discipline since its inception. Indeed, Troll's earliest "Landschaftökologie" used the most advanced geospatial technologies of his time: aerial photography. As modern landscape ecology developed in the early 1980s, it became clear that satellite-based remote sensing would play an integral role in quantifying landscape patterns and dynamics to elucidate the relationships between spatial patterns and ecological processes (Groom et al. 2006; Shao and Wu 2008). Indeed, remote sensing technologies remain one of the primary data sources for landscape analysis (Hay et al. 2001; Newton et al. 2009; Yu et al. 2019). In general, remote sensing technologies in landscape ecology have been used to develop land cover classifications from which additional analysis is conducted.

The issue can be exacerbated, though, because land cover classifications may be subjective based on the classification schemas, number of classes, and even source datasets selected (Figure 3; see also Franklin et al. 2015). Understanding accuracy and the uncertainty associated with such thematic classifications is paramount. Given the inherent limitations associated with such classifications, the risk of propagating errors in subsequent landscape analysis is high without due diligence (Shao and Wu 2008).). Scaling and resolution issues associated with the classification of satellite imagery must be analyzed, especially in relationship to the modifiable areal unit problem (MAUP) (Hay et al. 2001). Research has shown, for instance, that thematic resolution can change the number of classes represented and resulting spatial patterns on categorical maps, which can influence the landscape metrics (Buyantuyev and Wu 2007).

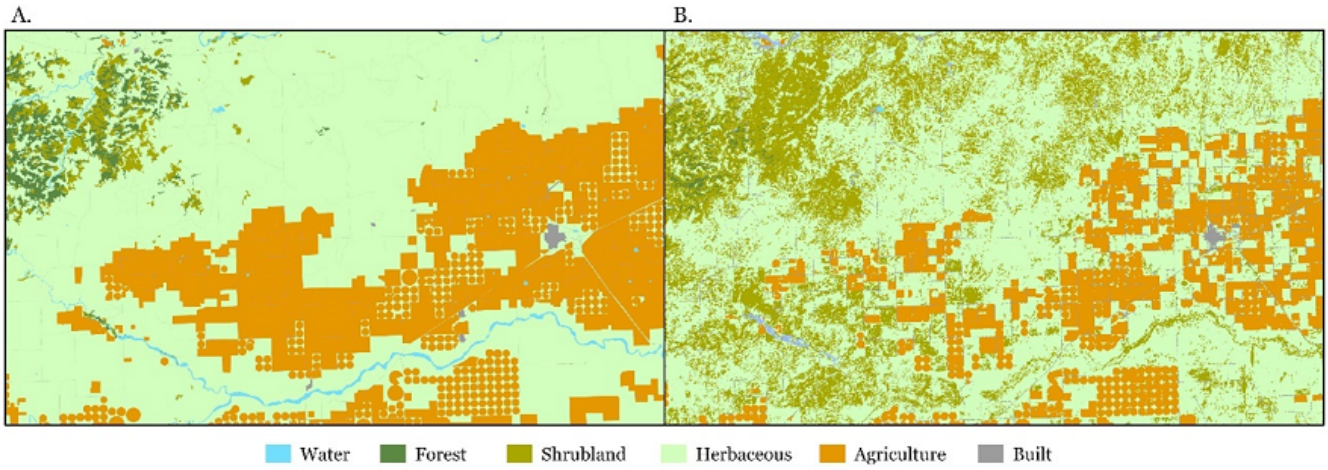


Figure 3A and 3B. Classified remotely sensed imagery is an important data source for landscape ecology analysis. However, errors in classification, resolution of the source data, and different classification methodologies and schemas used can influence the analysis. Here, two classified images of the same area, from the same time-period, and using the same classification schema are shown. However, the classifications were based on different source imagery and classification methods. 3A. utilized 1 m NAIP imagery, heads-up digitizing, image segmentation, and manual classification, while 3B. is reclassified National Land Cover Database data derived from 30 M Landsat data (Dewitz 2019). Source: authors.

Nonetheless, such derived datasets are integrated into geographic information systems (GIS) for further analysis. Indeed, the key role of GIS in landscape ecology research has long been recognized (Yu et al. 2019), and is perhaps best exemplified by the number of landscape metrics or indices that have been developed to quantify landscape patterns using GIS. Such indices measure characteristics of individual patches, classes (i.e. patch types), and/or the entire landscape. Compositional metrics include richness, evenness, and diversity measurements of individual patches or classes, while configurational elements may quantify patch size, shape, and density and isolation/proximity and connectivity of landscape elements. Again, though, the quality of the output is dependent on the accuracy of the input datasets. By quantifying such landscape characteristics in conjunction with other ecological properties, landscape ecologists may better understand the reciprocal relationship between landscape pattern and ecological processes.

Historically, these metrics were designed to quantify patterns in categorical maps (McGarigal et al. 2012). More recently, though, landscape metrics have been developed to quantify continuous (i.e. numerical values representing gradients (McGarigal 2009)) rather than discrete patterns across landscape and that consider the three-dimensional nature of landscape elements (Stupariu et al. 2017).

LiDAR and digital photogrammetry have also proven useful in landscape ecology. LiDAR, for instance, can be used to characterize landscape elements such as canopy cover (Wasserman et al. 2019) and vertical habitat structure to estimate animal species diversity (Simonson et al. 2014). Similarly, structure from motion (SfM), a photogrammetric technique that develops dense 3D point clouds from a sequence of 2D images, also shows promise as a relatively low-cost method to characterize landscape and habitat structure (Cunliffe et al. 2016).

Other uses of GIS&T in landscape ecology includes development of species distribution models (SDMs) to predict habitat suitability based on a range of environmental variables (Sofaer et al. 2019); assessments of landscape-level habitat vulnerability to climate change (Comer et al. 2019); and the incorporation of machine learning techniques, such as random forest, neural networks, and deep learning, to uncover complex ecological patterns (see Stupariu et al. 2021 for a review). Additionally, since quantification of spatial patterns is fundamental to landscape ecology, the use of a variety of spatial statistics, in addition to traditional landscape metrics, is important. Measurements of spatial autocorrelation are particularly important to assess the spatial heterogeneity of ecological data across space and along environmental gradients (Fortin 1999). Positive spatial autocorrelation, for instance, may reflect various biotic factors, such as habitat preference and conspecific attraction (Guélat and Kéry 2018), whereas negative spatial autocorrelation may reflect competition (Marthur 2015) or a disturbance event (Biswas et al. 2017). However, spatial autocorrelation indices are scale dependent and scale effects in spatial analysis must be considered (Qi and Wu 1996).

Global navigation satellite systems (GNSS), such as GPS, Galileo, and GLONASS, technologies have also been utilized in landscape ecology studies (e.g. Zavala and Zavala 1993; Kitron 1998). For instance, GNSS receivers and associated software can be used to augment aerial and satellite based measurements used for landscape studies or directly used to obtain point, line, or polygon features for incorporation in landscape studies (Farina 1998). Moreover, researchers can track animals with GNNS receivers to obtain accurate locational information on the movement of various animals in the landscape (e.g. Tomkiewicz et al. 2010).

Emerging geospatial technologies (Fagin et al. 2020), such as unoccupied aerial systems (UAS), on-demand micro- and nanosatellites, and ground-based sensors (Crowley and Cardille 2020), also may play a role. While remotely sensed data have long been valuable sources of information for mapping and understanding landscape patterns, the relatively coarse spatial and temporal resolution of traditional remotely sensed datasets may not adequately capture certain ecological patterns and processes, such as microhabitat, fine-scale disturbance, subtle phenological changes, successional rates, and various biophysical parameters (Wulder et al. 2004). While some of these limitations have been addressed with newer generation higher resolution sensors, cost constraints and data availability have limited their utility for many researchers (Anderson and Gaston 2013; Loarie et al. 2007). UAS and ground-based sensors are emerging geospatial technologies that may address some of these limitations by providing a relatively inexpensive, on-demand, fine spatial and temporal resolution remote sensing platform (Anderson and Gaston 2013; Christie et al. 2016).

4. The Future of GIS&T in Landscape Ecology

Landscape ecology is still a relatively new and emerging discipline in North America. Within little over four decades, though, it has gone from an obscure subdiscipline of ecology to an important field with concepts that permeate ecological and geographic research. Landscape ecological research is now conducted over a range of scales in terrestrial landscapes and, even, in aquatic habitats. Advances in space-borne technology, such as global navigation satellite systems (GNSS) and new remote sensors with both high spatial

and temporal resolution are contributing to advances in the field. New models, backed by powerful computing power, are adding to our understanding of landscape complexity. Lastly, in the face of global environmental change, landscape ecology has an important role to play in advancing our knowledge about the causes and consequences of these changes across a range of scales and systems. Coupled with GIS&T, landscape ecology will continue to play an important role in understanding, quantifying, predicting landscape heterogeneity and the ecological and socio-economic consequences thereof.

References

Anderson, B.J. (2008). Research in the journal Landscape Ecology, 1987-2005. Landscape Ecology. 23: 129-134.

Anderson, K., and Gaston, K.J. (2013) Lightweight unmanned aerial vehicles will revolutionize spatial ecology. Frontiers in Ecology and the Environment, 11(3):138-146.

Biswas, S.R., R.L. MacDonald, and H.Y.H. Chen. 2017. Disturbance Increases Negative Spatial Autocorrelation in Species Diversity. Landscape Ecology. 32(4). 823-834.

Biudes, M.S., N.G. Machado, V.H.M. Danelichen, M.C. Souza, G.L. Vourlitis, and J.D.S. Nogueira. (2014) Ground and remote sensing-based measurements of leaf area index in a transitional forest and seasonal flooded forest in Brazil. International Journal of Biometeorology. 58, 1181–1193 (2014).

Buyantuyev, A. and Wu, J. (2007). Effects of Thematic Resolution on Landscape Pattern Analysis. Landscape Ecology. 22: 7-13.

Christie, K.S., Gilbert, S.L. Brown, C.L., Hatfield, M., & Hanson, L. (2016). Unmanned aircraft systems in wildlife research: current and future applications of a transformative technology. Frontiers in Ecology and the Environment, 14(5), 241-251.

Comer, P.J., J.C. Hak, M.S. Reid, S. Auer, K. Schulz, H. Hamilton, R. Smyth, and M. Kling. (2019). Habitat Climate Change Vulnerability Index Applied to Major Vegetation Types in the Western Interior United States. Land. 8:108.

Crowley, M.A. and Cardille, J. A. (2020). Remote Sensing's Recent and Future Contributions to Landscape Ecology. Current Landscape Ecology Reports. 5: 45-57.

Cunliffe, A. M., Brazier, R. E., and Anderson, K. (2016). Ultra-Fine Grain Landscape-Scale Quantification of Dryland Vegetation Structure with Drone-Acquired Structure-from-Motion Photogrammetry. Remote Sensing of Environment. 183: 129-143.

Czerwinski, C.J., King, D. J., and Mitchell, S. W. (2014). Mapping Forest Growth and Decline in a Temperate Mixed Forest Using Temporal Trend Analysis of Landsat Imagery, 1987-2010. Remote Sensing of Environment. 141: 188-200.

ESA Vegetation Classification Panel. (2015). How a National Vegetation Classification Can Help Ecological Research and Management. Frontiers in Ecology and the

Environment. 13: 185–186.

Fagin, T. D., Wikle, T. A., and Mathews, A. J. (2020). Emerging Geospatial Technologies in Instruction and Research: An Assessment of U.S. and Canadian Geography Departments and Programs. The Professional Geographer. 72(4): 631-643.

Farina, A. (1998). Principals and Methods in Landscape Ecology. Springer Science-Business Media Dordrecht.

Forman, R. T. T. (1995). Land Mosaics. Cambridge: Cambridge University Press.

Forman, R. T. T. and Godron, M. (1986). Landscape Ecology. New York: John Wiley & Sons.

Fortin, M. J. (1999). Spatial Statistics in Landscape Ecology. In J.M. Klopatek and R.H. Gardner (eds.) Landscape Ecological Analysis: Issues and Applications. New York: Springer-Verlag. Pp. 253-279

Frazier, A. (2019). Landscape Metrics. The Geographic Information Science & Technology Body of Knowledge (2nd Quarter 2019 Edition), John P. Wilson (Ed.).

Groom, G., Mücher, C. A., Ihse, M., and Wrbka, T. (2006). Remote Sensing in Landscape Ecology: Experiences and Perspectives in a European Context. Landscape Ecology. 21: 391-408.

Guélat, J. and Kéry, M. (2018). Effects of Spatial Autocorrelation and Imperfect Detection on Species Distribution Models. Methods in Ecology and Evolution. 9(6): 1614-1625.

Hay, G., Marceau, D., Dubé, P, and Bochard, A. (2001). A Multiscale Framework for Landscape Analysis: Object-specific Analysis and Upscaling. Landscape Ecology 16: 471-490.

Hobbs, R. (1997). Future Landscapes and the Future of Landscape Ecology. Landscape and Urban Planning. 37: 1-9.

Kitron, U. (1998). Landscape Ecology and Epidemiology of Vector Born Diseases: Tool for Spatial Analysis. Journal of Medical Entomology. 4(1): 435-445.

Klijn, J. A. (1995). Hierarchical Concepts in Landscape Ecology and its Underlying Disciplines. Wageningen (The Netherlands), DLO Winand Staring Centre. Report 100, 144.

Levin, S. A. (1992). The Problem of Pattern and Scale in Ecology: The Robert H. MacArthur Award Lecture. Ecology. 73(6): 1943-1967.

Loarie, S.R., Joppa, L.N., & Pimm, S.L. (2007). Satellites miss environmental priorities. Trends in Ecology and Evolution, 22(12), 630-632.

MacArthur, R. H. and Wilson, E. O. (1967). The Theory of Island Biogeography. Princeton University Press. Princeton.

Marthur, M. (2015). Spatial Autocorrelation Analysis in Plant Population. An Overview. Journal of Applied and Natural Science. 7(1): 501-513.

McGarigal, K. (2014). Landscape Pattern Metrics. Wiley StatsRef: Statistics Reference Online.

McGarigal, K., Cushman, S. A., and Ene, E. (2012). FRAGSTATS v4: Spatial Pattern Analysis Program for Categorical and Continuous Maps. Computer software program produced by the authors at the University of Massachusetts, Amherst.

McGarigal, K., Tagil, S. & Cushman, S.A. (2009). Surface Metrics: An Alternative to Patch Metrics for the Quantification of Landscape Structure. Landscape Ecology. 24: 433-450.

Newton, A. C., Hill, R. A., Escheverría, C., Golicher, D., Benayas, J. M. R., Cayuela, L., and Hinsley, S. A. (2009). Remote Sensing and the Future of Landscape Ecology. Progress in Physical Geography. 33(4): 528-546.

Qi, Y. and Wu, J. (1996). Effects of Changing Spatial Resolution on the Results of Landscape Pattern Analysis Using Spatial Autocorrelation Indices. Landscape Ecology. 11(1): 39-49.

Rhemtulla, J. M., Mladenoff, D. J. (2007). Why history matters in landscape ecology. Landscape Ecology. 22:1–3.

Risser, P.G., Karr, J. R., and Forman, R. T. T. (1984). Landscape Ecology Directions and Approaches: A workshop held at Allerton Park Piatt County, Illinois April 1983. Illinois Natural History Survey Special Publication Number 2. Champaign, IL.

Shao, G. and Wu, J. (2008). On the Accuracy of Landscape Pattern Analysis Using Remote Sensing Data. Landscape Ecology. 23: 505-511.

Simonson, W.D., Allen, H. D., and Coomes, D. A. (2014). Applications of Airborne Lidar for the Assessment of Animal Species Diversity. Methods in Ecology and Evolution. 5: 719-729.

Sofaer, H.R., C.S. Jarnevich, I.S. Pearse, R.L. Smyth, S. Auer, G.L. Cook, T.C. Edwards, G.F. Guala, T.G. Howard, J.T. Morisette, and H. Hamiliton. (2019). Development and Delivery of Species Distribution Models to Inform Decision-Making. Bioscience. 69(7): 544-557.

Stupariu, M-S, Cushman, S. A., Plesoianu, A., Patru-Stupariu, I., and Fürst, C. (2021). Machine Learning in Landscape Ecological Analysis. A Review of Recent Approaches. Landscape Ecology.

Stupariu, M-S, I. Patru-Stupariu, I., and Timofte, C. (2017). 3D Landscape Metrics: What and How Can Be Computed. IALE 2017 European Landscape Ecology Congress. Ghent, September 12-15, 2017.

Tomkiewicz, S.M., Fuller, M. R., Kie, J. G., and Bates, K. K. (2010). Global Positioning System and Associated Technologies in Animal Behaviour and Ecological Research. Philosophical Transactions of the Royal Society B. 365: 2163-2776.

Troll, C. (1939). Luftbildplan und ökologische Bodenforschung. Sonderabdr. Berlin.

Troll, C. (1968). Landschaftsokologie. In Pflanzensoziologie und Landschaftsokologie –Symposium Stolzenau. Junk: The Hague. Pp. 1–21

Turner, M. G. (1989). Landscape Ecology: The Effect of Pattern on Process. Annual Review of Ecology and Systematics. 20: 171-197.

Turner, M. G. (2005). Landscape Ecology in North America: Past, Present, and Future. Ecology. 86(8): 1967-1974.

Turner, M. G., Gardner, R.H., and O'Neill, R. V. (1995). Ecological Dynamics at Broad Scales. Bioscience. 45: S29-S35.

Urban, D.L., R.V. O'Neill, and H.H. Shugart Jr. (1987). Landscape Ecology: A Hierarchical Perspective Can Help Scientists Understand Spatial Patterns. BioScience. 37(2): 119-127.

Wasserman, T. N., Sánchez Meador, A. J., and Waltz, A. E. M. (2019). Grain and Extent Considerations Are Integral for Monitoring Landscape-Scale Desired Conditions in Fire-Adapted Forests. Forests. 10(6): 465;

Wu, J. (2013). Key Concepts and Research Topics in Landscape Ecology Revisited: 30 Years After the Allerton Park Workshop. Landscape Ecology, 28: 1-11.

Wu, J. and Hobbs, R. (2007). Landscape Ecology: The state-of-the-science. In J. Wu and R. Hobbs (Eds.) Key Topics in Landscape Ecology. Cambridge University Press. Cambridge. Pp. 271-287.

Wulder, M.A., Hall, R.J., Coops, N.C., & Franklin, S.E. (2004). High Spatial Resolution Remotely Sensed Data for Ecosystem Characterization. BioScience 54(6): 511-521.

Yu, H. X. Liu, B. Kong, R. Li, and G. Wang. (2019). Landscape Ecology Development Supported by Geospatial Technologies: A Review. Ecological Informatics. 51: 185-192.

Zavala, I. and Zavala, M. A. (1993). Global Positioning System as a Tool for Ecosystem Studies at the Landscape Level: An Application in the Spanish Mediterranean. Landscape and Urban Planning. 24: 95-104.