

Open source landscape ecology tools

Maximillian H.K. Hesselbarth · Jakub
Nowosad · Author 3 · ... ·

Received: date / Accepted: date

Abstract max. (200 words) Abstract Abstract Abstract Abstract Abstract
Abstract Abstract Abstract Abstract Abstract Abstract Abstract Abstract
Abstract Abstract Abstract Abstract Abstract Abstract Abstract Abstract
Abstract Abstract Abstract Abstract Abstract Abstract Abstract Abstract
Abstract Abstract Abstract Abstract Abstract Abstract Abstract Abstract
Abstract Abstract Abstract Abstract Abstract Abstract Abstract Abstract
Abstract Abstract Abstract Abstract Abstract Abstract Abstract Abstract
Abstract Abstract Abstract Abstract Abstract Abstract Abstract Abstract
Abstract Abstract Abstract Abstract Abstract Abstract Abstract Abstract
Abstract Abstract Abstract Abstract Abstract Abstract Abstract Abstract
Abstract Abstract Abstract Abstract Abstract Abstract Abstract Abstract
Abstract Abstract Abstract Abstract Abstract Abstract Abstract Abstract
Abstract Abstract Abstract Abstract Abstract Abstract Abstract Abstract
Abstract Abstract Abstract Abstract Abstract Abstract Abstract Abstract
Abstract Abstract Abstract Abstract Abstract Abstract Abstract Abstract
Abstract Abstract Abstract Abstract Abstract Abstract Abstract Abstract

Grants or other notes about the article that should go on the front page should be placed here. General acknowledgments should be placed at the end of the article.

Maximillian H.K. Hesselbarth
Department of Ecosystem Modelling, University of Goettingen, Buesgenweg 4, 37077 Goettingen, Germany
E-mail: maximilian.hesselbarth@uni-goettingen.de

Jakub Nowosad
Institute of Geoecology and Geoinformation, Adam Mickiewicz University, Krygowskiego 10, 61-680 Poznan, Poland
E-mail: nowosad.jakub@gmail.com

Author 3
Adress author 3
E-mail: E-Mail author 3

...
...
E-mail: ...

Keywords keyword 1 · keyword 2 · keyword 3 · keyword 4 · . . . ·

1 Introduction

1.1 A short introduction to landscape ecology

Landscape ecology focuses on how ecological processes are influenced and modified by the heterogeneous landscapes they occur in and simultaneously how the ecological processes themselves influence the landscapes [1,2,3]. In this context, landscape ecology considers, besides others, i) spatial and temporal dynamics of heterogeneous landscapes, ii) interactions, fluxes and exchange within these landscapes, iii) how the landscapes influence ecological processes (and vice versa) and lastly iv) how to manage these heterogeneous landscapes [4,1].

While human activities have altered the landscapes for millennia [5,6], in the past centuries the effects of humans on landscapes have increased to an unknown high, known as the Anthropocene [7]. Today, almost all landscapes are directly or indirectly influenced by human activities [8]. Thus, understanding the complex interactions between landscapes and ecological processes becomes increasingly important [3].

Because landscapes are defined as mosaics of different land covers, ecosystems, habitat types, or land uses [9,10,11], spatial context is important and ecological processes will vary spatially [3]. Related to this, the importance of scale was already raised decades ago [12,13,14] and is still of relevance until today [15,16]. Thus, in contrast to many other sub-disciplines of ecology, landscape ecology emphasizes especially spatial patterns to a high degree [4]. Consequently, the field of landscape ecology relies on software to preprocess, modify, model, analyze and visualize spatial data.

1.2 Open-source software and R

Software to manage and analyze data becomes increasingly important in modern scientific research [17] and many scientific studies would not have been possible without open-source software [18]. Open-source software includes all software which is released under a license that allows to freely use, modify and distribute the software [19]. Open-source software development has many advantages, such as fast innovation, transparency and reliability as well as longevity mainly due to many diverse contributors [20,19]. Additionally, the use of open-source software facilitates (computational) reproducibility and can allow a better understanding of the methodology [18,21]. Lastly, open-source software allows other scientists to reuse code and not “reinvent the wheel” [18] and customize existing software to their specific needs easily [22].

One example of a successful open-source project is the *R* programming language and its *Comprehensive R Archive Network* (CRAN) for extensions

(also called packages) [23]. Firstly introduced in 1995 [24], today the programming language is among the most popular programming languages, especially in ecology [25]. Originally introduced as a statistical programming language, a growing body of packages designed to analyze spatial data subsequently emerged for the *R* programming language [26]. This is documented by the growing *CRAN Task View: Analysis of Spatial Data* [27] and *CRAN Task View: Handling and Analyzing Spatio-Temporal Data* [28] with currently almost 300 packages in total. The growing popularity of the *R* programming language for spatial data analysis and landscape ecology can also be seen by the increasing number of related textbooks [29,30,31].

Even though many other open-source tools for landscape ecology exist [32, 33,34], in this review we are going to focus on tools implemented in the *R* programming language. Thus, in the first part we are going to try to give a comprehensive overview over existing *R* packages for landscape ecology. In the second part, we will identify topics for which *R* packages are currently missing to the best of our knowledge. For more general overviews see e.g. [35,22,36, 37].

2 Existing packages

2.1 Basic spatial data

2.2 Creating maps

2.3 Spatial regression

2.4 Ecological analysis

Landscape metrics One of the most fundamental steps of landscape ecology is to describe and quantify landscape characteristics [2,38]. For discrete land cover classes the composition (number and abundance) and configuration (spatial arrangement) of the landscape is often described using landscape metrics [39,40,41,42]. These metrics allow to compare different landscapes, quantify temporal and spatial landscape changes and investigate interactions between landscape characteristics and ecological processes [40].

The use of landscape metrics was heavily facilitated by the introduction of the *FRAGSTATS* software [43], firstly published in 1995 [44,42]. However, *FRAGSTATS* is not open-source software (however it is free to download at the developers' homepage), which restricts transparency and reproducibility. To provide a truly open-source solution to calculate landscape metrics, recently the *landscapemetrics* package [45] was developed. The package allows to calculate the most widely used landscape metrics in a transparent and reproducible workflow within the *R* environment.

Species distribution modeling Species distribution modeling (SDM) analysis how landscape patterns (e.g. habitat suitability, resources availability, etc.)

influence and determine the patterns of species distribution, mainly to infer ecological processes and predict future species distributions [46]. Originated in the 1970s, SDM has experienced numerous methodological advancement and a numerous body of literature exists today [47]. Additionally, textbooks introducing basic concepts of SDM in R exists [48, 29].

Because the used modeling approaches are diverse [49, 50, 29], there is also a large number of *R* packages used for SDMs. Popular approaches and packages include generalized linear models using e.g. the *stats* package; generalized additive models using e.g. the *mgcv* or *lme4* package; classification and regression trees (CART) using e.g. the *rpart*, *randomForest* or *ranger* package or multivariate data analysis using e.g. the *ade4* package. Another widely used SDM approach uses the concept of maximum entropy [51, 29]. However, currently the *maxent* package is not available on *CRAN* anymore. Of course, also packages specifically designed for SDM exists. This includes the *dismo*, *sdm*, *ecospat*, *biomod2* and *PresenceAbsence* packages.

Connectivity Connectivity is one of the core elements of landscape structure [52] and thus one of the core concepts of landscape ecology [3]. Landscape connectivity describes how landscape characteristics facilitate or hinder the movement of species [53] or other aspects of mobility, such as dispersal, gene or nutrient flow [3]. While structural connectivity focuses only on landscape characteristics (e.g. movement corridors, barriers, etc.), functional connectivity also includes behavior characteristics of the species [53, 3].

Given its wide concept, many different measures of connectivity exists [54]. On patch level structural connectivity can be measured using nearest-neighbor distances or characterizations of the patch neighborhood (e.g. amount of suitable habitat) [54, 3]. Such measures are provided within the *landscapemetrics* package (see 2.4). Another way to describe connectivity is based on graph theory with the advantages that also functional connectivity can be included [54]. In graph theory [55] landscapes are described by nodes (i.e. habitat patches) connected by and functional connections called links [55]. The *grainscape* package [56] provides a tool to model connectivity based on spatially explicit networks. More general, the *igraph* packages [57] provides functionality related to graph theory.

Landscape genetics Landscape genetics investigates how characteristics of landscapes interact with gene flow, genetic drift and selection [58]. Such insights improve our understanding of metapopulation dynamics, speciation, species' distributions and conservation [59]. By explicitly including characteristics of landscape, landscape genetics is a way more realistic way of analysis than e.g. metapopulation genetics [60]. As a result of its interdisciplinary, landscape genetics combines methods from different disciplines including landscape ecology, spatial statistics, geography and population genetics [59].

Neutral landscape models

References

1. M. Turner, Landscape ecology: The effect of pattern on process, *Annual Review of Ecology and Systematics* **20**(1), 171 (1989)
2. M. Turner, Landscape ecology: What is the state of the science?, *Annual Review of Ecology, Evolution, and Systematics* **36**(1), 319 (2005)
3. K. With, *Essentials of Landscape Ecology*, 1st edn. (Oxford University Press, Oxford, UK, 2019)
4. P. Risser, J. Karr, R. Forman, Landscape ecology: Directions and approaches, *Illinois Natural History Survey Special Publication* **2**, 7 (1984)
5. E. Ellis, Anthropogenic transformation of the terrestrial biosphere, *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* **369**(1938), 1010 (2011)
6. E. Ellis, Ecology in an anthropogenic biosphere, *Ecological Monographs* **85**(3), 287 (2015)
7. P. Crutzen, Geology of mankind, *Nature* **415**(6867), 23 (2002)
8. P. Vitousek, Human Domination of Earth's ecosystems, *Science* **277**(5325), 494 (1997)
9. R. Forman, M. Godron, *Landscape Ecology* (Wiley, New York, 1986)
10. R. Forman, *Land Mosaics: The Ecology of Landscapes and Regions* (Cambridge University Press, Cambridge, UK, 1995)
11. J. Wiens, in *Mosaic Landscapes and Ecological Processes*, ed. by L. Hansson, L. Fahrig, G. Merriam (Chapman and Hall, London, UK, 1995), pp. 1–26
12. J. Wiens, Spatial scaling in ecology, *Functional Ecology* **3**(4), 385 (1989)
13. S. Levin, The problem of pattern and scale in ecology, *Ecology* **73**(6), 1943 (1992)
14. D. Jelinski, J. Wu, The modifiable areal unit problem and implications for landscape ecology, *Landscape Ecology* **11**(3), 129 (1996)
15. P. Šímová, K. Gdulová, Landscape indices behavior: A review of scale effects, *Applied Geography* **34**, 385 (2012)
16. L. Estes, P. Elsen, T. Treuer, L. Ahmed, K. Caylor, J. Chang, J. Choi, E. Ellis, The spatial and temporal domains of modern ecology, *Nature Ecology & Evolution* **2**(5), 819 (2018)
17. G. Wilson, D. Aruliah, C. Brown, N. Chue Hong, M. Davis, R. Guy, S. Haddock, K. Huff, I. Mitchell, M. Plumbley, B. Waugh, E. White, P. Wilson, Best Practices for Scientific Computing, *PLoS Biology* **12**(1), e1001745 (2014)
18. A. Prlić, J. Procter, Ten simple rules for the open development of scientific software, *PLoS Computational Biology* **8**(12), e1002802 (2012)
19. A. St. Laurent, *Understanding Open Source and Free Software Licensing* (O'Reilly, Sebastopol, USA, 2008)
20. G. von Krogh, E. von Hippel, The promise of research on open source software, *Management Science* **52**(7), 975 (2006)
21. S. Powers, S. Hampton, Open science, reproducibility, and transparency in ecology, *Ecological Applications* **29**(1) (2019)
22. S. Steiniger, G. Hay, Free and open source geographic information tools for landscape ecology, *Ecological Informatics* **4**(4), 183 (2009)
23. R Core Team. R: A language and environment for statistical computing. R Foundation for Statistical Computing (2019)
24. D. Smith. Over 16 years of R Project history (2016)
25. J. Lai, C. Lortie, R. Muenchen, J. Yang, K. Ma, Evaluating the popularity of R in ecology, *Ecosphere* **10**(1) (2019)
26. R. Bivand, Implementing spatial data analysis software tools in R, *Geographical Analysis* **38**(1), 23 (2006)
27. R. Bivand. Analysis of Spatial Data (2019)
28. E. Pebesma. Handling and Analyzing Spatio-Temporal Data (2020)
29. R. Fletcher, M.J. Fortin, *Spatial Ecology and Conservation Modeling: Applications with R*, 1st edn. (Springer, New York, USA, 2019)
30. R. Lovelace, J. Nowosad, J. Münchow, *Geocomputation with R*, 1st edn. (Chapman and Hall/CRC Press, Boca Raton, USA, 2019)
31. E. Pebesma, R. Bivand, *Spatial Data Science* (2019)

32. QGIS Development Team. QGIS (2016)
33. GRASS Development Team. Geographic Resources Analysis Support System (GRASS). Open Source Geospatial Foundation (2017)
34. C. Porta, L. Spano, F. Pontedera. R.li - Toolset for multiscale analysis of landscape structure <<https://grass.osgeo.org/grass74/manuals/r.li.html>> (2017)
35. A. Jolma, D. Ames, N. Horning, H. Mitsova, M. Neteler, A. Racicot, T. Sutton, Chapter Ten: Free and open source geospatial tools for environmental modeling and management, *Developments in Integrated Environmental Assessment* **3**, 163 (2008). DOI 10.1016/S1574-101X(08)00610-8
36. S. Steiniger, E. Bocher, An overview on current free and open source desktop GIS developments, *International Journal of Geographical Information Science* **23**(10), 1345 (2009)
37. S. István, Comparison of the most popular open-source GIS software in the field of landscape ecology, *Landscape & Environment* **6**(2), 76 (2012)
38. A. Lausch, T. Blaschke, D. Haase, F. Herzog, R. Syrbe, L. Tischendorf, U. Walz, Understanding and quantifying landscape structure - A review on relevant process characteristics, data models and landscape metrics, *Ecological Modelling* **295**, 31 (2015)
39. E. Gustafson, Quantifying landscape spatial pattern: What is the state of the art?, *Ecosystems* **1**, 143 (1998)
40. E. Uuemaa, M. Antrop, R. Marja, J. Roosaare, Ü. Mander, Landscape metrics and indices: An overview of their use in landscape research, *Living Reviews in Landscape Research* **3**, 1 (2009)
41. E. Uuemaa, Ü. Mander, R. Marja, Trends in the use of landscape spatial metrics as landscape indicators: A review, *Ecological Indicators* **28**, 100 (2013)
42. E. Gustafson, How has the state-of-the-art for quantification of landscape pattern advanced in the twenty-first century?, *Landscape Ecology* **34**, 1 (2019)
43. K. McGarigal, S. Cushman, E. Ene. FRAGSTATS v4: Spatial pattern analysis program for categorical and continuous maps. Computer software program produced by the authors at the University of Massachusetts, Amherst. <<http://www.umass.edu/landeco/research/fragstats/fragstats.html>>. University of Massachusetts (2012)
44. J.A. Kupfer, Landscape ecology and biogeography: Rethinking landscape metrics in a post-FRAGSTATS landscape, *Progress in Physical Geography* **36**(3), 400 (2012)
45. M. Hesselbarth, M. Sciaini, K. With, K. Wiegand, J. Nowosad, Landscapemetrics: An open-source R tool to calculate landscape metrics, *Ecography* **42**(10), 1648 (2019)
46. Y. Wiersma, F. Huettmann, C. Drew, in *Predictive Species and Habitat Modeling in Landscape Ecology*, ed. by C. Drew, Y. Wiersma, F. Huettmann (Springer New York, New York, USA, 2011), pp. 1–6. DOI 10.1007/978-1-4419-7390-0_1
47. N. Zimmermann, T. Edwards, C. Graham, P. Pearman, J.C. Svenning, New trends in species distribution modelling, *Ecography* **33**(6), 985 (2010)
48. A. Guisan, W. Thuiller, N. Zimmermann, *Habitat Suitability and Distribution Models: With Applications in R*, 1st edn. (Cambridge University Press, Cambridge, UK, 2017). DOI 10.1017/9781139028271
49. M. Hooten, in *Predictive Species and Habitat Modeling in Landscape Ecology*, ed. by C. Drew, Y. Wiersma, F. Huettmann (Springer New York, New York, USA, 2011), pp. 29–41. DOI 10.1007/978-1-4419-7390-0_3
50. J. Kerr, M. Kulkarni, A. Algar, in *Predictive Species and Habitat Modeling in Landscape Ecology*, ed. by C. Drew, Y. Wiersma, F. Huettmann (Springer New York, New York, USA, 2011), pp. 9–28. DOI 10.1007/978-1-4419-7390-0_2
51. S. Phillips, R. Anderson, R. Schapire, Maximum entropy modeling of species geographic distributions, *Ecological Modelling* **190**(3–4), 231 (2006)
52. P. Taylor, L. Fahrig, K. Henein, G. Merriam, Connectivity is a vital element of landscape structure, *Oikos* **68**(3), 571 (1993)
53. L. Tischendorf, L. Fahrig, On the usage and measurement of landscape connectivity, *Oikos* **90**(1), 7 (2000)
54. P. Kindlmann, F. Burel, Connectivity measures: A review, *Landscape Ecology* pp. s10,980–008–9245–4 (2008)
55. A. Laita, J. Kotiaho, M. Mönkkönen, Graph-theoretic connectivity measures: What do they tell us about connectivity?, *Landscape Ecology* **26**(7), 951 (2011)

-
56. A. Chubaty, P. Galpern, S. Doctolero, The R toolbox grainscape for modelling and visualizing landscape connectivity using spatially explicit networks, *Methods in Ecology and Evolution* **11**(4), 591 (2020)
 57. G. Csardi, T. Nepusz, The igraph software package for complex network research, *InterJournal Complex Systems*, 1695 (2006)
 58. S. Manel, M. Schwartz, G. Luikart, P. Taberlet, Landscape genetics: Combining landscape ecology and population genetics, *Trends in Ecology & Evolution* **18**(4), 189 (2003)
 59. A. Storfer, M. Murphy, J. Evans, C. Goldberg, S. Robinson, S. Spear, R. Dezzani, E. Delmelle, L. Vierling, L. Waits, Putting the ‘landscape’ in landscape genetics, *Heredity* **98**(3), 128 (2007)
 60. R. Holderegger, H. Wagner, A brief guide to landscape genetics, *Landscape Ecology* **21**(6), 793 (2006)