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Open-source tools in R for landscape ecology

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Abstract max. (200 words) Abstract

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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 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 millenniums [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 vary spatially [3]. 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 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 that is released under licenses that allow to use, modify and distribute the software [19]. Open-source software development has many advantages, such as fast innovation, transparency, reliability, and 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 used methodology of a study [18,21]. Furthermore, open-source software

allows other scientists to reuse code and not "reinvent the wheel" [18] by customizing existing software to their specific needs [22]. Last but not least, even though not strictly necessary by definition [22,23], most open-source software is also free-of-cost, which allows using the software without any costs in contrast to often expensive proprietary software [20,22,23]. This democratize scientific research as free-of-cost software removes one gatekeeper for researches without access to proprietary software.

One successful example of an open-source project is the *R* programming language, and its extensions called packages [24]. Firstly released in 1995 [25], today the programming language is among the most popular programming languages, especially in ecology [26]. Originally introduced as a statistical programming language, a growing body of packages designed to analyze spatial data subsequently emerged for the *R* programming language [27,28]. The expanding CRAN Task Views document this: *Analysis of Spatial Data* [29] and *Handling and Analyzing Spatio-Temporal Data* [30] currently list about 300 packages in total. Since the task views are maintained manually by just a few people, the actual amount of *R* packages related to spatial data is most likely even higher. The growing popularity of the *R* programming language for spatial data analysis and landscape ecology can also be seen with the increasing number of related textbooks [31,28,32]. A recent overview over the progress of *R* to handle spatial data in general can be found in [33].

The growing body of *R* packages related to spatial data processing and analysis results in a high capability of this language for landscape ecology. Even though many other open-source tools for landscape ecology exist [34,35, 36], in this review, we focus on software implemented in the *R* programming language. For more general overviews of open-source software for landscape ecology see [37,22,23,38]. Because in addition to handling spatial data, also tasks such as statistical modeling, creation of publication-ready figures, and even preparation of complete reports can be done in the same working environment (Fig. 1), the *R* programming language can be a very powerful tool. Thus, in the first part, we present an overview of existing *R* packages for landscape ecology (Table 1). In the second part, we present a survey in which we asked the community how they currently use the *R* programming language and to identify topics for which *R* packages are presently missing for landscape ecology.

2 Existing packages

Most *R* packages are developed and maintained by the community, which shows how open-source software development can facilitate innovation, reproducibility, and reuse of code. There are three major online platforms to host *R* packages and make them accessible to potential users: CRAN, GitHub, and Bioconductor. The last one focuses on tools for the analysis of genomic data; therefore, we focus on only the former two in this review. CRAN (the *Comprehensive R Archive Network*) provides large visibility to the community, ease

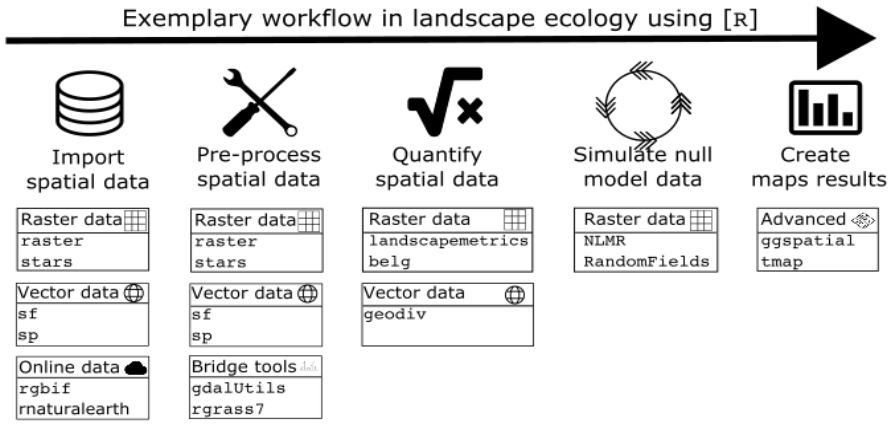

Fig. 1: Exemplary workflow of spatial data analyses for landscape ecology using the R programming language. For all major tasks, a few example R packages are listed. .

of installation, and a technical quality standard, including checks for common problems on all major operating systems [39]. *GitHub* hosts source code under version control, and allows users to install packages with one line of code using the *remotes* [40] package. Additionally, hosting a package on *GitHub* provides many useful features to collaborate and communicate between developers and users [39], or integrated unit testing.

The guaranteed technical quality standard on *CRAN* requires more initial work for developers compared to *GitHub*, while it ensures for users that the package can be installed on their machine. Additionally, the technical quality standard on *CRAN* also facilitates reproducibility and reuse of code, as shown by many reverse dependencies of *R* packages, i.e., package x requires and uses code from package y [20,19,22,18,21]. CRAN also provides archived versions of outdated or orphaned packages and thus ensuring long term availability of code. Thus, most packages can be found on both platforms, and many developers use *GitHub* for regular development and *CRAN* to publish stable releases of the packages. Furthermore, communities like *rOpenSci* also provide a peer review process for code quality. For more information about *R* package development, see [39].

2.1 Spatial data representations

While *R* has several build-in data structures, including vectors, matrices, data.frames, and lists, it has no internal support for reading, processing, or visualizing spatial data. However, because there is a substantial interest in spatial data analysis, support for spatial data is now provided by many *R* packages ([28], page 10). Most spatial data belong to one of two data models, namely

spatial raster and spatial vector model, and both data models have several implementations in the *R* language. Importantly, main *R* packages for spatial data use the external *GDAL* and *PROJ* libraries, which allow for reading and writing of hundreds of spatial data formats, and coordinates transformation. Additionally, *R* allows for conversion between data models and specific implementations, which can be useful if given methods only exist for a particular data model or implementation.

In the raster data model, surfaces are divided into cells, where each cell stores a numeric value. The values could represent discrete phenomena, such as a class number of a land cover category, or continuous phenomena, such as elevation values. Currently, the most prominent package allowing for raster data representation is *raster* [41]. A *raster* successor, *terra*, aimed at the simpler interface and improved performance is now being developed [42]; however, it could take several years for this package to be adopted by other developers and users. Alternatively, the *stars* package can be used to read and process raster data focusing on spatial-temporal data cubes [43]. Additionally, there are packages that improve some basics raster operations in terms of computational performance or compatibility between raster and vector operations, such as *fasterize* [44], *rasterDT* [45], or *exactextractr* [46].

The vector data model consists of two main elements i) geometries (such as points, lines, polygons) and ii) attributes, where each geometry is connected to a row in the attribute table. In many cases, this data model allows a more realistic representation of landscape features, however, with the cost of higher computational demands . The *sp* package was the standard for vector data representation for more than ten years [47,48]. As of 2020, more than 500 *R* packages directly depend or imports *sp*. However, *sp* is not actively developed anymore, and its recommended successor is the *sf* package [49].

2.2 Spatial data download

Nowadays, spatial data for many scales is available from an abundance of online-accessible sources. A lot of this data is publicly available, either as a direct download or through an API connection, and several packages can use this to download the spatial data directly into an *R* session. Since publicly available data is becoming more prominent, so are *R* packages to access them. Packages include *rnaturalearth* [50] to access the Natural Earth database, the *elevatr* package to access raster elevation data [51], the *rgbif* to access the Global Biodiversity Information Facility (GBIF) portal [52], the *BIEN* package [53] to access the Botanical Information and Ecology Network Database, the *marmap* to download bathymetry data from the ETOPO1 database [54], or the *FedData* package [55] to access the National Land Cover Database (NLCD) data for the USA. Furthermore, the *getlandsat* package [56] allows to download data from the Landsat 8, the *MODIS* package [57] to download MODIS products, and *sen2r* [58] to download Sentinel-2 optical images. Also, the `getData()` function from the *raster* package allows to download climatic and bioclimatic

data from WorldClim v1.4 (for WorldClim v2, see the in-development package *geodata*). Additionally, the *rgee* package [59] gives access to an extensive catalog of data from Google Earth Engine, including climate data, land cover maps, and satellite imagery.

2.3 Spatial data processing

Coordinate references systems (CRS) describe how spatial data is projected from the earth's three-dimensional surface to a two-dimensional surface as required for spatial analysis or creating maps . This is also referred to as the spatial projection and is often the first barrier in spatial data analysis. It is not only required to have all of the used data in the same projection, but also to select a proper CRS. This is of importance because the projection into a two-dimensional surface unavoidable leads to distortion, and different CRS are optimized for different properties, regions of the world, and scales . Coordinates in spatial data represent one of many coordinate reference systems. Two main groups of CRS, namely geographical and projected, exist, with each having many members. In the first one, geographical, positions are specified by latitude and longitude coordinates in degrees. However, most landscape ecology studies should utilize projected CRSs, which use some measurement units (e.g., meters). The selection of projected CRS should be based on the property of spatial data that we want to keep intact (e.g., does not distort areas, shapes, distances, or angles) and be appropriate for a given study area. Tools to find an appropriate CRS for a certain region can be found at `https://spatialreference.org`, `https://epsg.org`, or `http://epsg.io`. All packages from Section 2.1 have interfaces for coordinates transformations, allowing to unify spatial projections when the used data have different CRS.

A second common spatial data processing task is required when the available data extends over a larger area than the study region. In this case, the pre-processing of spatial data should include vector clipping or raster cropping. Related to that, masking certain areas of the study region can be required by using, e.g., certain spatial filters such as water bodies. Packages from Section 2.1 also allow for these operations. Additionally, they offer many other operations, such as merging or joining spatial data, extracting values from one dataset into another, raster resolution changes, or vector data simplifications. A comprehensive collection of methods to aggregate raster values to a coarser resolution can also be found in the *grainchanger* package [60]. Furthermore, *landscapetools* is a collection of various utility functions for the raster data model [61].

Finally, there is a number of tools for landscape ecology implemented in GIS software, such as r.li or r.pi for GRASS GIS [62,63,36], terrain analysis methods in SAGA GIS [64], or morphological operations for Google Earth Engine. Gladly, it is possible to control several GIS software directly from R

using dedicated packages, such as *rgrass7* [65] for GRASS GIS, *RSAGA* [66] for SAGA GIS, and *rgee* [59] for Google Earth Engine.

2.4 Creating maps

Creating maps is essential when working with spatial data. It has a role in checking the spatial and value-related quality of data, data exploration, and finally communicating results. *R* allows to create two major types of maps. Firstly, static maps in which the developer has full control over the presentation of the map and secondly, interactive maps in which the user has the possibility to modify the map by e.g. changing the displayed values. All packages listed in Section 2.1 have build-in methods for plotting spatial data using the generic `plot()` function. However, the generic functions are focused on quick visual inspection of the data, rather than the creating complete maps.

The *tmap* package provides a coherent plotting system for static and interactive maps that is based on the layered grammar of graphics [67] and aims for creating publication-ready maps. Static thematic maps, including proportional symbols, choropleth, or typology maps, can be created with the *cartography* package [68]. Also the popular plotting package *ggplot2* [69] has an extension especially designed for plotting spatial data named *ggspatial* [70]. Quick interactive visualization of spatial data can be done with the *mapview* package[71]. Both, *tmap* and *mapview* build upon the *leaflet* package and leaflet javascript library [72].

A slightly different approach to visualizing spatial data is adapted by the *rayshader* package [73] that creates topographic 2D and 3D maps.

2.5 Ecological analysis

Quantify landscape characteristics One of the most fundamental steps of landscape ecology analyses is to describe and quantify landscape characteristics [2, 74]. For discrete land cover classes, the composition (number and abundance) and configuration (spatial arrangement) of the landscape are often described using landscape metrics [75,76,77,78]. These metrics allow to compare different landscapes, quantify temporal and spatial landscape changes and investigate interactions between landscape characteristics and ecological processes [76].

The introduction of the *FRAGSTATS* in 1995 heavily facilitated the use of landscape metrics software [79,80,78]. However, while *FRAGSTATS* is free to download at the developers' homepage, it is not open-source software. This restricts its transparency, reproducibility, and extensibility. Recently the *landscapemetrics* package [81] was developed to provide a truly open-source solution to calculate landscape metrics. The package allows calculating the most widely used landscape metrics in a transparent and reproducible workflow within the *R* environment.

More recently, surface metrics were suggested as an alternative to landscape metrics for continuous raster data [82]. The *geodiv* package [83] allows to calculate gradient surface metrics to characterize continuous analysis of landscape features. Additionally, the *belg* package allows calculating the Boltzmann entropy of a landscape gradient [84].

Most landscape metrics are a single number depicting specific characteristics of a local landscape. Another possibility is to derive spatial signatures - a multi-value representation of landscape composition and configuration, such as a co-occurrence histogram. Spatial signatures calculated for many landscapes can be compared using one of the existing distance measures. This enables several types of spatial analysis on categorical raster data, such as searching for similar landscapes, detecting changes between landscape patterns, and spatial clustering of landscapes based on their composition and configuration. All of the methods mentioned above are implemented in the *motif* package [85].

Species distribution modeling Species distribution modeling (SDM) examine how landscape patterns (e.g., habitat suitability or resources availability) influence and determine the patterns of species distribution, mainly to infer ecological processes and predict future species distributions [86]. Originated in the 1970s, SDM has experienced numerous methodological advancement, and a numerous body of literature exists today [87]. Additionally, textbooks introducing basic concepts of SDM in *R* exists [88,31].

Because the used modeling approaches are diverse [89,90,31], 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* [24] package; generalized additive models using, e.g., the *mgcv* [91] or *lme4* [92] package; classification and regression trees (CART) using, e.g., the *rpart* [93], *randomForest* [94] or *ranger* [95] package or multivariate data analysis using , e.g., the *ade4* [96] or *vegan* [97] package. Also, packages specifically designed for SDM exists, including includes the *dismo* [98], *sdm* [99], *ecospat* [100], *biomod2* [101], *PresenceAbsence* [102], or *zoon* [103] packages. Related to SDM, there are several packages to estimate home ranges and habitat selection, including *adehabitatHR* and *adehabitatHS* [104] or *amt [105]*

Connectivity Connectivity is one of the core elements of landscape structure [106] and thus one of the core concepts of landscape ecology [3]. Landscape connectivity describes how landscape characteristics facilitate or hinder the movement of species [107] 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), functional connectivity also includes behavior characteristics of the species [107,3]. Given its broad concept, many different measures of connectivity exist [108]. On patch level, structural connectivity can be measured using nearest-neighbor distances or characterizations of the patch neighborhood (e.g., amount of suitable habitat) [108,3]. Such measures are provided within the *landscapemetrics* package (see 2.5). Furthermore, the *lconnect* package [109] and *Makurhini* package [110] provide

several landscape connectivity metrics. Another way to describe connectivity is based on graph theory with the advantage that functional connectivity can also be included [108]. In graph theory [111], landscapes are described by nodes (i.e., habitat patches) connected by and functional connections called links (or edges) [111]. The *grainscape* package [112] provides a tool to model connectivity based on spatially explicit networks. More general, the *igraph* package [113] provides functionality related to graph theory. Resistance surfaces and least-cost paths are other tools to model functional connectivity. The resistance surface describes the effects of facilitating or hindering the landscape's characteristics for an organism moving within it [114]. Least-cost paths can be calculated using the *gdistance* package [115]. Absorbing Markov chains that combine random walk theory and mortality based on the landscape characteristics [116] and is provided by the recently published *samc* package [117].

Landscape genetics Landscape genetics investigates how characteristics of landscapes interact with gene flow, genetic drift, and selection [118]. Such insights improve our understanding of metapopulation dynamics, speciation, species' distributions, and conservation [119]. By explicitly including landscape characteristics, landscape genetics is a way more realistic way of analysis than, e.g., metapopulation genetics [120]. As a result of its interdisciplinary, landscape genetics combines methods from different disciplines, including landscape ecology, spatial statistics, geography, and population genetics [119].

Since describing connectivity between two locations is one of the fundamental steps of landscape genetics, all packages useful for connectivity (see 2.5) are also important for landscape genetics. Further functionality for landscape genetics can be found in the *graphs4lg* [121], *PopGenReport* [122,123], *HierDpart* packages [124], or *GeNetIt* [125].

Neutral landscape models Neutral landscape models are used to create structured landscapes in the absence of specific ecological and landscape processes as null models against which hypotheses including specific ecological and landscape processes can be tested statistically [126,127]. Because neutral landscape models are not based on ecological and landscape processes, many different generic algorithms to create landscapes can be found across various *R* packages. A comprehensive collection of algorithms to simulate neutral landscape models specifically designed for landscape ecology can be found in the *NLMR* package [61]. Furthermore, the *RandomFields* package [128] allows to simulate Gaussian fields, which could be used as neutral landscape models.

Various

3 Survey of R usage by landscape ecology community

To better understand how the landscape ecology community uses* R*, we conducted a short survey and used mailing lists and social media to reach the

Table 1: Overview of commonly used R packages for landscape ecology. Packages are sorted by their major application task. Only packages focused on spatial data and landscape ecology are included.

Task	R package	Reference
Spatial data	raster	[41]
	terra	[42]
	stars	[43]
	fasterize	[44]
	rasterDT	[45]
	exactextractr	[46]
	sp	[47,48]
	sf	[49]
Spatial data download	rnaturalearth	[50]
	elevatr	[51]
	rgbif	[52]
	BIEN	[53]
	marmap	[54]
	FedData	[55]
	getlandsat	[56]
	MODIS	[57]
	sen2r	[58]
Creating maps	mapview	[71]
	tmap	[67]
	leaflet	[72]
	cartography	[68]
	ggspatial	[129]
	rayshader	[73]
Quantifying landscape characteristics	landscapemetrics	[81]
	belg	[84]
	motif	[85]
	geodiv	[83]
Species distribution modeling	dismo	[98]
	sdm	[99]
	ecospat	[100]
	biomod2	[101]
	PresenceAbsence	[102]
	zoon	[103]
	adehabitatHR, adehabitatHS	[104]
	amt	[105]
Connectivity	lconnect	[109]
	Makurhini	[110]
	grainscape	[112]
	gdistance	[115]
	samc	[117]
Landscape genetics	raphs4lg	[121]
	PopGenReport	[122,123]
	HierDpart	[124]
	GeNetIt	[125]
various	NLMR	[61]
	RandomFields	[128]
	landscapetools	[61]
	grainchanger	[60]

community. In total, the survey was answered by 103 participants, of which the the majority were either "PhD students" (34%), followed by "Post-Docs" (28.2%) and "Professors" (12.6%). Other, less frequent answers were "Data scientists", "None of the above", "Government employees" "Master's degree student" and "Bachelor's degree student" (in decreasing order).

Most people use *R* either "daily" (54.4%) or a "few times a week" (36.9%). Almost half of all participants described themselves as "advanced" users (46.6%), while 40.8% described themselves as "intermediate" users. Related to this, about half of the participants either implemented their own package (21.4%) or plan to do so in the future (23.3%) and most of these packages are hosted on *GitHub* and/or *CRAN*.

We asked the participants to select which terms describe their research topics the best, and options that were selected by more than 10% of participants included "biodiversity", followed by "land use management", "landscape connectivity", and "nature conservation" (Fig. 2 A)).

Next, we were interested in the most important tasks to the workflow of the participants. Not surprisingly, "(pre-)processing of data", "spatial statistics", and "creating maps" were the most selected options (Fig. 2 B)). Interestingly, the available options seemed to describe the most important task to the workflow quite well since only very few participants selected the "others" option (all options with less than five total answers were classified as "others").

Interestingly, more people use the raster data model (72.8%) in comparison to the vector data model (27.2%). This was also represented in the most used *R* packages (Fig. 2 C)). When asked for the three most used packages, participants of the survey listed 83 packages in total. The *raster* package was mentioned the most, followed by the *sf* package. Both packages are designed for basic and advanced data handling and processing of raster and vector data, respectively, representing the results of Fig. 2 C). Nevertheless, the large availability and usage of different *R* packages across the community can be seen in the large "others" option (packages mentioned by less than 5 participants; 33.44%).

Lastly, when asked how useful *R* is currently for landscape ecology, the vast majority of participants answered with either "very useful" or "useful" (summarized 91.26%) and only only very few participants evaluated *R* as "intermediate", "not useful" or "not useful at all" (summarized 8.74%; Fig. 2 D)).

The survey also included a section in which participants could list methods and tools currently missing in *R* and answers to this question were very diverse.

Overall, 22.3% of the participants reported that currently no packages and functionality are missing for them or they lack the overview to answer the question. There were three most common topics across the answers of the participants. Firstly, many participants (13.6%) wished for a better computational performance of *R* in terms of speed and required RAM, especially for larger data. Secondly, participants are missing specific approaches to quantify landscape characteristics (such as surface metrics), or are wishing for an improvement of currently available approaches to quantify landscape characteris-

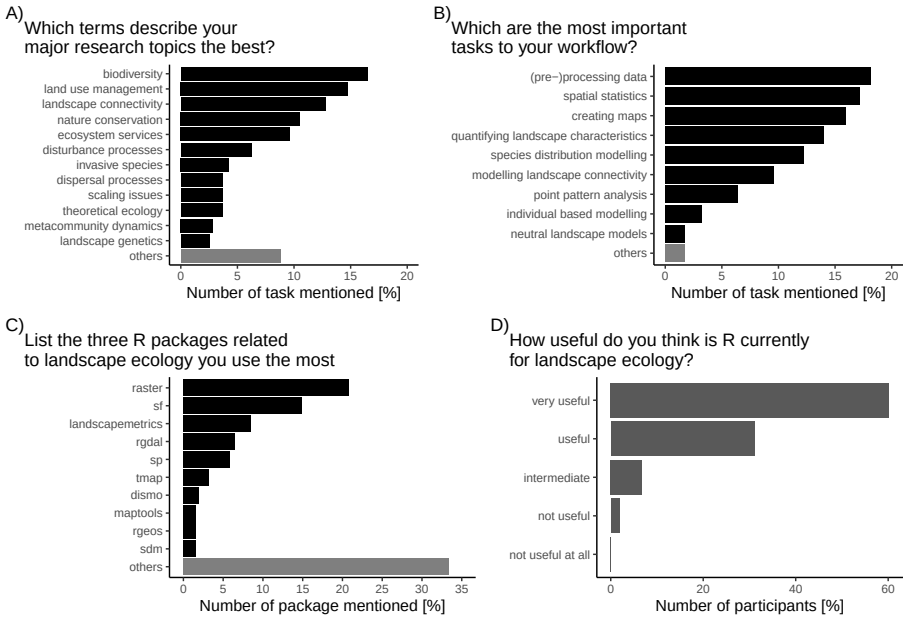

Fig. 2: Results of the online survey about open-source software tools in R for landscape ecology. Results include A) which terms describe major reserach topics the best, B) the most important workflow task, C) the most used R packages and D) the overall usefulnes or R for landscape ecology. The 'others' category includes all answers with less than five total mentions.

tics (9.7%). Thirdly, many participants (8.7%) are currently missing advanced and easy-to-apply methods to create high-quality maps or other visualization-related functionality.

4 Conclusions

Since its first introduction in 1995, *R* has come a long way from an exclusively statistical programming language to a powerful landscape ecology tool. Today, many *R* packages, mainly developed by the community itself, provide a vast collection of functions and algorithms aimed at spatial data handling and analysis. The highly dynamic development of *R* packages for landscape ecology also shows the strength of open-source software with its high innovation, transparency, reliability, and longevity. However, since landscape ecology constantly develops and improves, the *R* programming language and its packages need to change and adapt to these changes.

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Conflict of interest MHKH and JN are authors of the *landscapemetrics* and *landscapetools* package. JN is author of *belg* and *motif* package.

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Author contributions MHKH and JN designed the survey form and analyzed the responses of the participants. MHKH and JN drafted the manuscript and all authors contributed critically to the manuscript and gave final approval for publication. We used the 'sequence–determines–credit' approach (SDC) for the sequence of authors.

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