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Software note

pastclim 1.2: an R package to easily access and use paleoclimatic reconstructions

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The recent development of continuous paleoclimatic reconstructions covering hundreds of thousands of years paved the way for a large number of studies from disciplines ranging from paleoecology to archaeology, conservation to population genetics, macroevolution to anthropology and human evolution to linguistics. Unfortunately, (paleo)climatic data can be challenging to extract and analyze for scholars unfamiliar with such specific file formats.

Here we present *pastclim*, an R package facilitating the access and use of paleoclimatic reconstructions. It currently includes two of such datasets, covering respectively the last 120 000 and 800 000 years, and a vignette provides instructions on how to include additional datasets.

The package contains a set of functions to quickly and easily recover the climate for time periods of interest either for the whole world or specific areas, extract data from locations scattered in space and/or time, retrieve time series from individual sites, and manage the ice or land coverage, offering a handy platform to include the climate of the past into existing or new analyses and pipelines.

Keywords: evolutionary biology, paleoclimate, paleoecology, R package

Background

Many research fields, such as ecology and archaeology, use climate reconstructions to contextualize information, e.g. the presence of a species at a given location in the past. Reconstructions for certain time points, like the last glacial maximum or Holocene, have been published and made available for a number of climate models (Braconnot et al. 2012, Lima-Ribeiro et al. 2015, Schmatz et al. 2015, Kageyama et al. 2021). However, certain analyses necessitate time series, and over the last few years a few datasets that provide climate reconstructions through time have become available (Fordham et al. 2017, Armstrong et al. 2019, Holden et al. 2019, Beyer et al. 2020, Brown et al. 2020, Karger et al. 2021, Krapp et al. 2021, Timmermann et al. 2022).

The availability of such data paved the way for a large number of research questions among many disciplines, i.e. ecology (Miller et al. 2021b, VanBuren and Jarzyna 2022), paleoecology (Leonardi et al. 2018, 2020, Somveille et al. 2020, Chen et al. 2021, Schap et al. 2021, Thorup et al. 2021, Medina-Castañeda et al. 2022, Reade et al. 2022), conservation (Beyer and Manica 2021), population genetics (Maisano Delser et al. 2021, Miller et al. 2021a, Warmuth et al. 2021), archaeology (Betti et al. 2020, Racimo et al. 2020, Beyer et al. 2021, Krzyzanska et al. 2021, Bradshaw et al. 2022, Cerasoni et al. 2022, Park and Marwick 2022, Timbrell et al. 2022), macroevolution of different taxa, including the genus *Homo* (Saupe et al. 2014, Will et al. 2021, Fordham et al. 2022, Timmermann et al. 2022, Troyer et al. 2022), anthropology (Leonardi et al. 2017, Padilla-Iglesias et al. 2022) and linguistics (Beyer et al. 2019).

A challenge for the use of such climatic datasets covering time series is that they are large in size, and they require the use of specialized software to manipulate and extract the data. Climate reconstructions are generally stored in the netCDF format, and the *cdo* (Schulzweida 2021) tools in bash, and their implementations in R and Python can be used to access the data. Software designed to handle raster data, such as the R packages *raster* (Hijmans 2022a), and *terra* (Hijmans 2022b), can extract data from netCDF files, but dealing with files containing hundreds of time steps and dozens of variables can be challenging. Furthermore, different authors have packaged their data in different ways, either as a single netCDF file, or broken down into multiple files that must be downloaded from various public repositories. The naming of variables is also often inconsistent, adding a further challenge for users.

Here we present *pastclim*, an R package specifically designed to download and manipulate paleoclimatic datasets. Natively, it includes two such sets: one from Beyer et al. (2020), covering the last 120 000 years at intervals of 1000–2000 years based on Global Circulation Models HadCM3 (Singarayer and Valdes 2010) and HadAM3H (Valdes et al. 2017), and one from Krapp et al. (2021), covering the last 800 000 years at intervals of 1000 years based on a statistical approach to reconstruct HadCM3 outputs.

The package is supported by a website (https://rdrr.io/github/EvolEcolGroup/pastclim) which includes several vignettes (section 'Articles') detailing how to use the functions, and a cheatsheet that provides an overview of the key functions. The functions of the package are generic and can be used to process similar data. A specific vignette (available from the package website or as detailed in Box 1) explains how to format and use custom datasets in *pastclim*. It also provides instructions on how such additional dataset can be officially included in the package, and we expect the number of reconstructions available to grow steadily.

Data description

Natively, *pastclim* allows direct access to two datasets: 'Beyer2020' covering the last 120 000 years (Beyer et al. 2020); 'Krapp2021' going back to 800 000 years ago (Krapp et al. 2021). Both must be downloaded using the *download_dataset()* function from the package. Additionally, a small 'Example' dataset, which includes a few time points from Beyer2020, is included in the package for use in the vignette and tests, and does not need to be downloaded.

The Beyer2020 and Krapp2021 datasets (Box 1) include 17 annual bioclimatic variables, respectively 4 and 6 monthly bioclimatic variables, annual net primary productivity (NPP), leaf area index (only for Beyer2020), land masks and ice sheets. They also contain biome reconstructions, a categorical variable representing the type of natural vegetation, reconstructed by the BIOME4 model (Kaplan et al. 2003). In addition to the variables presented in the original publications (Beyer et al. 2020, Krapp et al. 2021), the updated datasets now also include two measures of topography based on the ETOPO1 dataset (NOAA National Geophysical Data Center 2009): altitude and rugosity (Box 1). The latter was calculated as the standard deviation of the altitude of all above-water $1' \times 1'$ cells included in each of the $0.5° \times 0.5°$ cells as used in the climate reconstructions.

For both datasets the variables are bias-corrected and downscaled at a spatial resolution of $0.5° \times 0.5°$ (for details on these processes see the original publications). Furthermore, using the ice sheet reconstructions specific to those two datasets (see the relevant publications for details on the models used to define the ice sheets), we masked regions under the ice caps: reconstructions under ice caps are not useful for most ecological and archaeo/anthropological analyses and masking such large datasets can be time-consuming. The Caspian and Black Seas were excluded from all time slices based on their current extent, all other internal water bodies (including the Aral Sea and the Garabogazköl lagoon) are not masked.

The original Beyer2020 and Krapp2021 datasets are freely available to download from Figshare (https://figshare.com/articles/dataset/LateQuaternary_Environment_nc/12293345/4) and OSF (https://osf.io/8n43x/). They are stored in two different ways, for Beyer2020 as a large netcdf file containing most variables (plus an additional small file for some vegetation variables); and for Krapp2021 as separate netcdf files for each variable. The repackaged data for the two datasets are found on https://figshare.com/articles/dataset/pastclim_beyer2020_v1_0_0/19723405 and https://figshare.com/articles/dataset/pastclim_krapp2021_v1_0_0/19733680).

An up-to-date list of all datasets included in *pastclim* can be accessed through the command *get_available_datasets()*. Detailed information on them can be obtained from the help for each dataset, e.g. *help("Beyer2020")*. *pastclim* relies on reconstructions being made publicly available, and it is important that users cite the original sources of the data so that data producers get the appropriate recognition.

Methods and features

The *pastclim* package allows users to download and manage the datasets using a unified interface. The user can store the

Box 1 Characteristics of the two native databases accessible from pastclim and main functions of pastclim. A full list of the functions available can be found in the documentation.

Annual climatic variables	bio01: Annual mean temperature bio04: Temperature seasonality bio05: Minimum annual temperature bio06: Maximum annual temperature bio07: Temperature annual range bio08: Mean temperature of the wettest quarter bio09: Mean temperature of driest quarter bio10: Mean temperature of warmest quarter bio11: Mean temperature of coldest quarter bio12: Annual precipitation bio13: Precipitation of wettest month bio14: Precipitation of driest month bio15: Precipitation seasonality bio16: Precipitation of wettest quarter bio17: Precipitation of driest quarter bio18: Precipitation of warmest quarter bio19: Precipitation of coldest quarter
Monthly bioclimatic variables	Temperature Precipitation Cloudiness Relative humidity (Beyer2020 only) Wind speed (Beyer2020 only) Net primary productivity
Vegetation variables	Net primary productivity Leaf area index (Beyer2020 only) Biome (including ice masks)
Topography variables	Altitude Rugosity Land masks
Time slices	Beyer2020: Every 1000 years between the present and 22 000 BP, every 2000 years between 22 000 BP and 120 000 BP Krapp2021: Every 1000 years between the present and 800 000 BP

Download the data	
get_data_path()	Retrieve the path in which pastclim automatically stores the data
set_data_path()	Store the data in a custom path
download_dataset()	Download a whole dataset (all variables available)
get_vars_for_dataset()	Download variables of choice for a given dataset
get_downloaded_datasets()	Summary of the downloaded variables
get_time_steps()	List of time steps available in a given dataset
Get climate for locations or regions	
location_slice()	Get the climate for given locations (by coordinates and age)
location_series()	Get time series of the climate for given locations
region_slice()	get the climate for a given region in a given time step
sample_region_slice()	sample a given number of points from the climate of a region
region_series()	get the time series of the climate for a given region
sample_region_series()	sample a given series of points from the time series of a region
Working with biomes and ice sheets	
get_biome_classes()	legend of the 'biome' categorical variable, when available
get_ice_mask()	get a mask with the extent of the ice sheets for a given time step
get_land_mask()	get a mask with the extent of the land masses for a given time step
Vignettes	
vignette("pastclim_overview", package = "pastclim")	overview of *pastclim*
vignette("custom_datasets", package = "pastclim")	how to add a new dataset to *pastclim*
vignette("available_datasets", package = "pastclim")	list of datasets available

data within the package itself (default option) and find them automatically without the need of setting a path. The path in which the data are saved can be retrieved using the function *get_data_path()*. It is also possible to store the datasets in a custom directory using *set_data_path()*.

We envision two main uses for *pastclim*. On one hand, a user might have one (or a few locations) of interest for which they want to retrieve a time series of bioclimatic variables. Under this scenario, such time series are simply retrieved through the function *location_series()* (Box 1), and they can be compared to other information for those sites. In Applied example 1 (Supporting information) we provide a step-by-step commented code illustrating how (zoo)archaeologists might use *pastclim* to provide context for their habitat reconstructions based on faunal data from different stratigraphic layers of a site.

The other use we envisage is for larger-scale analyses, where a user might be interested in climatic reconstructions for several sites, likely sampled at different times, and possibly contrast this information with the background climate across a whole region. In *pastclim*, the functions *location_slice ()* and *region_slice()* (Box 1) provide these functionalities. The code detailed in Applied example 2 (Supporting information) shows how these functions can be combined to explore the bioclimatic niche of a species.

With these functions, data can also be easily cropped to preset geographic extents or masks representing specific continental masses. We also include helper functions facilitating data manipulation and visualization (Box 1).

Furthermore, climatic fluctuations not only led to changes in the bioclimatic variables but also affected the extent of the permanent ice sheets and the sea levels, hence modifying the coastlines. In *pastclim* it is possible to get the ice and land masks for a given time slice using the functions *get_ice_mask()* and *get_land_mask()*. For details on how such extents were defined, see the original publications, as different modelling efforts have taken potentially different approaches. As mentioned earlier, note that, for Beyer2020 and Krapp2021, the bioclimatic variables are not provided for cells that were under either water or ice sheets.

When it is useful to subdivide the data into marine isotope stages (MIS), *pastclim* offers the function *get_mis_time_steps()* to get a list of time steps available for a given MIS, based on the subdivision proposed by (Lisiecki and Raymo 2005). This can be used to split the climatic reconstructions into MIS to perform basic plotting or further analyses.

Examples

Applied example 1: Extract the paleoclimate for a single site with dated stratigraphic layers

The first example (the code is freely available in the Supporting information) shows how to use *pastclim* to extract the paleoclimate for a single archaeological site with dated stratigraphic layers, i.e. in one location for multiple time slices. The aim is to find how habitat reconstructions from vertebrate faunal data compare with climate reconstructions from *pastclim*. Chronometric dates for the archaeological deposits containing vertebrate faunal remains from Contrebandiers Cave, Morocco, was extracted from (Dibble et al. 2012). Each identified species of Artiodactyla from Contrebandiers Cave was assigned a habitat and feeding preference. The relative abundance of forest, savanna and mixed forest/savanna Artiodactyla species was calculated for each archaeological layer following the number of identified species presented in Hallett (2018) (Fig. 1).

The input (Supporting information) is a table containing time (i.e. the chronometric age of the stratigraphic layer) and the relative percentage frequency of savanna, mixed and forest Artiodactyla species. Climate can then be extracted for each layer with faunal data using the decimal coordinates of Contrebandiers Cave. As shown in Fig. 1, annual precipitation more closely follows the trajectory of change in Artiodactyla habitat types than the mean temperature of the warmest quarter. In this example, vertebrate faunal data as a proxy for past habitat reconstructions agrees well with the annual precipitation extracted from *pastclim*.

Applied example 2: Analyze multiple sites scattered in space and time

The second example shows how to use *pastclim* to analyze a larger number of sites with lower individual coverage, i.e. several points scattered in space and time. The analyses focus on comparing the climate associated with observations to the one from the whole region of interest, and they may represent exploratory steps prior to species distribution modelling (Miller et al. 2021b).

The input (Supporting information) is a table containing calibrated radiocarbon dates associated with horse remains from two time steps (10 000 and 20 000 years ago) in Europe, with the associated geographic coordinates and site names (extracted from Leonardi et al. 2020) (Fig. 1). The analyses are performed using the 'Example' climatic dataset.

After transforming the calibrated radiocarbon dates into the associated time steps, it is straightforward to download the bioclimatic variables associated with the observations using *climate_for_locations ()*. It is then necessary to retrieve climatic information for the background, which can be done with the *climate_for_time_slice()* function. As the observations only cover Europe, it will be necessary to crop the resulting climatic reconstruction to the right extent, that is already available within *pastclim* together with other macroareas worldwide (e.g. Asia, Africa, Oceania, etc.).

The outputs are given as tables and hence can be easily manipulated to perform standard analyses. For example, it is possible to compare in a lot of different ways the climate associated with horse occurrences and the whole of Europe. The code (Supporting information) shows how to produce a PCA and a multiplot comparing the density for each variable in Europe and in the horse data (Fig. 1). This can be very useful, as the variables for which the distribution in the species differs from the distribution in the background are likely to play a bigger role in defining where a species can live (Miller et al. 2021b).

For species-distribution-model-like analyses (Elith and Leathwick 2009) it may be necessary to remove climatic variables showing a correlation in the data above a certain threshold (e.g. 0.7, Guisan et al. 2017). Given the standard format of the outputs from *pastclim*, it is straightforward to calculate the cross-correlation between the climatic variables in the observations and remove highly correlated ones, as detailed in the associated code (Fig. 1).

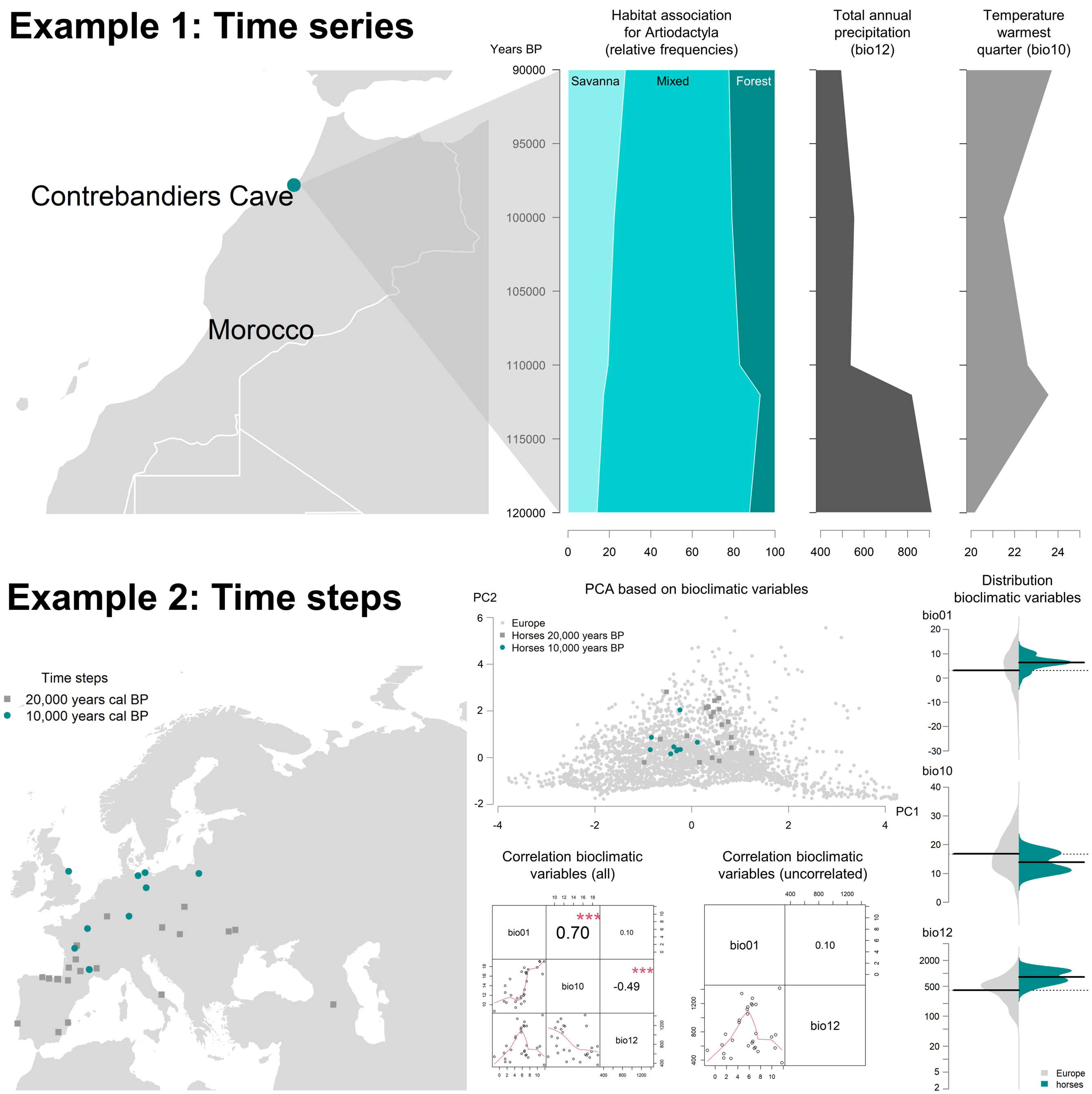

Figure 1. Outputs of Examples 1 and 2. Example 1: Location of Contrebandiers Cave, Morocco; relative abundance of habitat associated with Artiodactyla between 120 000 and 90 000 years ago; Variation of climatic variables through time between 120 000 and 90 000 years ago. Example 2: Map of the horse observations used for the analyses; principal component analysis based on bioclimatic variables; correlation between climatic variables in locations occupied by horses (both time steps); distribution of climatic variables in locations occupied by horses (right, in color) and in the whole of Europe (left, light gray) (both time steps). The data and code to run the examples are available in the supplementary material.

Discussion

The *pastclim* package offers scholars studying the distant past (e.g. archaeologists, archeozoologists, paleoecologists, evolutionary biologists) easily accessible paleoclimate variables. Past changes in climate are often presented as the drivers of technological innovation and cultural change within archaeology (Richerson et al. 2009, Taller and Conard 2022). However, climate reconstructions of the past are often based on proxy data from locations distant from an archaeological site (as discussed in Jacobs et al. 2012, Burke et al. 2021). Local, site-specific climate reconstructions give archaeologists the opportunity to see how changes in climate and/or biome align with changes in human behavior for a given location.

Climatic changes have also played a (sometimes major) role in the macroevolution of several species, including humans (Saupe et al. 2014, Will et al. 2021, Fordham et al. 2022, Timmermann et al. 2022, Troyer et al. 2022). Integrating the climate of the past into evolutionary biology studies can help gaining a better understanding of its impact in macroevolutionary dynamics such as adaptation, speciation and extinction (Hagen 2022).

Moreover, past climatic fluctuations heavily influenced the distribution and demography of humans and animals (Leonardi et al. 2018, Mondanaro et al. 2020, Fordham et al. 2022, Rodríguez et al. 2022, Timmermann et al. 2022). This is why *pastclim* can be a useful resource for scholars working in the field of (archeo)genomics, as it allows to easily extract climatic data to be integrated with genetic and genomic evidence when reconstructing the past (Lorenzen et al. 2011, Leonardi et al. 2017, Racimo et al. 2020, Theodoridis et al. 2020, Maisano Delser et al. 2021, Miller et al. 2021a).

Finally, the current rate of climatic changes due to human activity (Quintero and Wiens 2013) brings up the urgent need to understand how species react to climatic changes. Paleoclimate can be used as a virtual lab to 1) assess the extent to which species are able to change their ecological niche in response to environmental turnovers (Leonardi et al. 2020); 2) estimate the existing niche (Jackson and Overpeck 2000) though time, which can help to identify potentially suitable areas not apparent from the current distribution; 3) identify Anthropocene refugia i.e. areas that provide protection from human activities and will remain suitable in the long-term (Monsarrat et al. 2019); 4) more in general, gain a better understanding of the biological processes that allow surviving abrupt environmental changes (Fordham et al. 2020) which in turn may help to define better conservation strategies for the future.

Package installation and availability

This package and the associated vignette and examples are free and open-source, and available for download on the GitHub page of the Evolutionary Ecology Group https://github.com/EvolEcolGroup/pastclim, containing all details about the license and the dependencies. The associated website (https://rdrr.io/github/EvolEcolGroup/pastclim) provides a manual, vignettes and a cheatsheet.

To cite *pastclim* 1.2 or acknowledge its use, cite this Software note as follows, substituting the version of the application that you used for 'version 1.0':

Leonardi, M. et al. 2022. *pastclim* 1.2: an R package to easily access and use paleoclimatic reconstructions. – Ecography 2022: 1–9 (ver. 1.0).

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Author contributions

Michela Leonardi: Conceptualization (supporting); Data curation (supporting); Formal analysis (lead); Funding acquisition (supporting); Methodology (supporting); Software (supporting); Visualization (lead); Writing – original draft (lead); Writing – review and editing (lead). **Emily Hallett**: Conceptualization (supporting); Data curation (supporting); Formal analysis (supporting); Methodology (supporting); Software (supporting); Visualization (supporting); Writing – original draft (supporting); Writing – review and editing (supporting). **Robert Beyer**: Conceptualization (supporting); Data curation (lead); Methodology (lead); Writing – original draft (supporting); Writing – review and editing (supporting). **Mario Krapp**: Conceptualization (supporting); Data curation (lead); Methodology (lead); Writing – original draft (supporting); Writing – review and editing (supporting). **Andrea Manica**: Conceptualization (lead); Data curation (supporting); Formal analysis (supporting); Funding acquisition (lead); Methodology (lead); Project administration (lead); Resources (lead); Software (lead); Visualization (supporting); Writing – original draft (lead); Writing – review and editing (lead).

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Data availability statement

Data are available from the Figshare Repository: https://doi.org/10.6084/m9.figshare.21388545.v3 (Leonardi et al. 2022).

Supporting information

The input data and commented code for the applied examples are available at: https://doi.org/10.6084/m9.figshare.21388545.v3.

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