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Software note

GuidosToolbox Workbench: spatial analysis of raster maps for ecological applications

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Ecography
2022: e05864
doi: 10.1111/ecog.05864

Subject Editor: Brody Sandel
Editor-in-Chief: Miguel Araújo
Accepted 11 January 2022

Ecologists use a wide variety of metrics and software tools to quantify and map spatial patterns in ecological data. For analysis of categorical raster data, we introduce the GuidosToolbox Workbench (GWB), a series of Linux-based command-line modules, implementing popular algorithms from the interactive GuidosToolbox desktop application. We provide an overview of the workbench design, features of the individual modules, and an example implementation on the FAO SEPAL cloud computing environment.

Keywords: environmental monitoring, software, spatial analysis

Background

A wide variety of techniques are available to analyze the spatial patterns of ecological data. In the field of landscape ecology, which focuses on relationships between spatial pattern and ecological process, the historical focus of pattern analysis is on raster maps using landscape pattern metrics (Turner 1989). The general goals of such an analysis are to quantify and map various aspects of landscape patterns, to identify the spatial scale domains over which the patterns exist, and to locate where and how the patterns change over time (Riitters 2019). The metrics are motivated by conceptual models such as the patch-mosaic model (Forman and Godron 1981), fractal geometry (Milne 1992) and graph theory (Urban and Keitt 2001), scale domains are determined by varying the scale parameters of a metric (Dungan et al. 2002), and the pattern mapping portrays metric values as a descriptor of the contents of a given area of interest (e.g. a map tile) or as a descriptor of the neighborhood context of a given geographic location (e.g. a pixel) (Baker and Cai 1992). Different types of models and metrics employ raster data that can be discrete data (e.g. categorical maps) or continuous data (e.g. intensity maps). These and other aspects of landscape pattern analysis have been reviewed recently (Kupfer 2012, Lausch et al. 2015, Frazier and Kendron 2017, Keeley et al. 2021) and pattern analysis remains a vibrant area of research in landscape ecology today (Costanza et al. 2019).

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The earliest freely available software was designed as add-ons to geographic information systems (Baker and Cai 1992, McGarigal and Marks 1995). In the past decade, the growing popularity of open-source computing environments such as the R System (<www.r-project.org>) has prompted an astounding increase of spatial analysis software that cannot be adequately reviewed in this space (but see, for example, <https://rspatial.org/> and Dempsey 2019). Concurrently and in direct support of forest sector reporting in Europe and North America, the GuidosToolbox (GTB) was developed as a graphical user interface (GUI) to morphological spatial pattern analysis of raster data (Soille and Vogt 2009). GTB has since been enhanced with numerous, GTB-unique modules for analysis of landscape objects, patterns and networks, and specialized modules for assessing fragmentation and restoration (Vogt and Riitters 2017). GTB has gained global acceptance as a free, intuitive, interactive and generic standalone image analysis platform available for the three operating systems Linux, macOS and Microsoft Windows. Here we introduce the GuidosToolbox Workbench (GWB), which provides the most popular GTB modules as command line scripts on 64-bit Linux systems. The command-line setup permits non-interactive, un-supervised processing. This setup is implemented for the Linux environment, well-known for its resource efficient processing including taking advantage of multiple CPUs, which is ideal for implementation on webservers or workstations, typically running the Linux operating system. However, GWB can also be used on a PC or laptop. Because GWB is a subset of GTB, a new user is advised to first explore and gain confidence with the interactive GTB before implementing operational processing with GWB.

The installed GWB is completely self-contained in a single directory, which allows the use of the software in restricted computing environments. The default system-wide installation and maintenance is facilitated via the provision of custom installation packages for the Linux distributions Fedora, PCLinuxOS, Mageia, SUSE, Ubuntu and Debian as well as a generic installer package for other Linux distributions. The project homepage (<https://forest.jrc.ec.europa.eu/en/activities/lpa/gwb/>) provides links to installation instructions, license conditions (free for non-commercial use) and the changelog. All installation packages include the source code written in Bash and IDL (<www.l3harrisgeospatial.com/Software-Technology/IDL>) and two example GeoTIFF images to test all GWB modules. The following section describes the program setup and the features of the individual modules.

Methods and features

GWB is set up fully autonomous in a single directory `GWB`, which, in a system-wide installation is extracted into the operating system directory `/opt`:

- `input` and `output`: These directories contain the working setup to be copied by the user into the user's home account using the terminal command: `cp -fr /opt/GWB/*put ~/`. The directory `input` contains module-specific parameter files, two example GeoTIFF images used in the demonstrations below, and the file `readme.txt` with additional information. The directory `input` has a subdirectory `backup` containing copies of all the original parameter files. This subdirectory may also be used to store images that should be temporarily excluded from processing. The directory `output` is empty and will host the resulting files after processing. The default input and output directory name and locations can be changed by the user.
- `tools`: This directory contains program documentation, IDL runtime and libraries, the full IDL source code for each module, and compiled IDL and C executables.
- `check4updates`: A Bash-script to test for program updates.
- `GWB*`: Bash-scripts to launch the individual GWB modules; the script `GWB` lists all GWB modules.

All GWB-modules (Table 1) require single-band input images in the data type byte (unsigned 8-bit). Most modules need pseudo binary images with the mandatory assignment of 2-byte for foreground objects (objects of interest), 1-byte for the background and optional 0-byte assigned to missing pixels or no data. Further details on the methodology, input/output options and example applications are provided in the module-specific product sheets, see section Supporting information.

Each GWB module applies the settings defined in the module-specific parameter file to all GeoTIFF images found in the directory `input`. Images in a different format, and

Table 1. Summary of GWB modules and processing purpose.

GWB module	Description
GWB_ACC	Accounting of foreground objects
GWB_DIST	Euclidean distance of foreground and background objects
GWB_FAD	Fragmentation analysis at five fixed observation scales
GWB_FRAG	Fragmentation analysis at a user-defined observation scale
GWB_LM	Landscape mosaic analysis at a user-defined observation scale
GWB_MSPA	Morphological spatial pattern analysis of foreground objects
GWB_SPA	Simplified pattern analysis of foreground objects
GWB_P223	Density, contagion or adjacency of foreground objects
GWB_PARC	Parcellation of foreground objects
GWB_RSS	Restoration status summary of the network of foreground objects
GWB_REC	Recoding of pixel values in the input image

images not compatible with the selected analysis module, will be skipped automatically. The module-specific results are written into the directory `output`. Details on each image processing result can be found in the log-file in the directory `output`. The output distance and area measures are calculated in pixel units; it is therefore crucial to use input images in equal-area projection. The processing sequence for all GWB-modules is exemplified in Fig. 1 for the module `GWB_ACC` (below):

1) Place all GeoTIFF images in the directory `input`. Then verify or amend the settings in the file `<module>-parameters.txt`.
2) Run the GWB-module of interest specifying the location of `input` and `output` directory.
3) Find the log-file and the results, grouped for each input image in the directory `output`.

The following paragraphs provide a brief summary of the individual modules, resulting in spatially explicit maps and tabular summary statistics.

`GWB_ACC` conducts the accounting analysis. It will label and calculate the area of all foreground objects. The user can specify area thresholds resulting in up to six foreground object size classes, which are displayed with specific colors in the map product. The latter is accompanied by a statistical summary on the occurrence frequency, area and proportions of each object size class. Because largest objects are often of highest interest, the three largest objects are shown in pink color and listed separately at the end of the statistical summary file.

`GWB_DIST` conducts the Euclidean distance analysis. On the output map, each pixel shows the shortest distance to the foreground boundary. Pixels inside a foreground object have a positive distance value while background pixels have a negative distance value. Spatially explicit per-pixel distance values are shown in a pseudo-elevation color map. Positive values are associated with 'land', negative values with 'sea' and a value of zero corresponds to the 'coast line' (the foreground–background boundary).

`GWB_FAD` conducts a fragmentation analysis based on the foreground area density in neighborhoods surrounding the foreground pixels (Riitters et al. 2002). Because fragmentation is scale-dependent, it is reported at five observation scales defined by the size (in pixel units) of a moving window. The default observation scales are arbitrary, yet selected to allow comparisons across orders-of-magnitude scale differences irrespective of the spatial resolution of the input map. Fragmentation is measured by first determining the foreground area density (FAD) surrounding each foreground pixel (within each of five local neighborhoods that define observation scales). Threshold FAD values are then used to classify foreground pixels into several fragmentation classes. The user has the choice to conduct the fragmentation analysis at pixel-level or at foreground patch-level and to select reporting thresholds producing 6, 5 or 2 fragmentation classes.

`GWB_FRAG` conducts a similar fragmentation analysis but allows the user to specify a single (or multiple) specific observation scale.

`GWB_LM` conducts the landscape mosaic analysis at a user-defined observation scale. The landscape mosaic (Riitters et al.

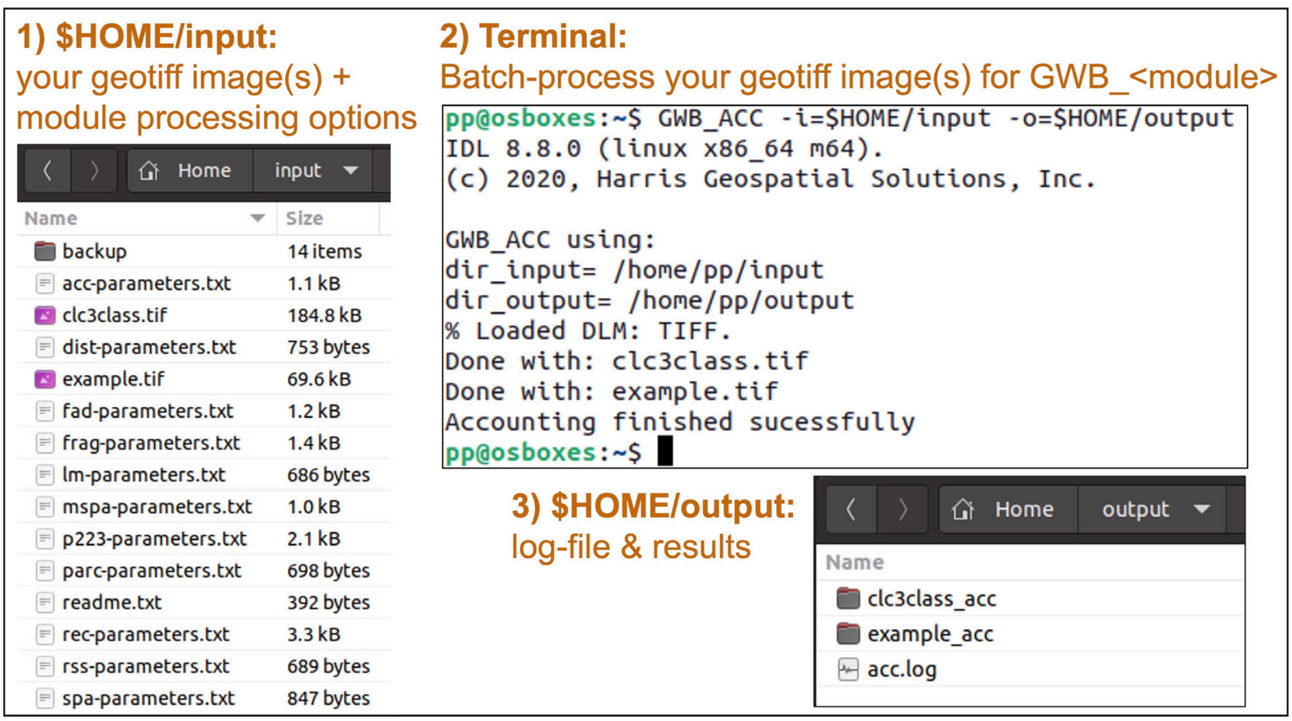

Figure 1. Processing procedure for all GWB-modules, here exemplified for accounting (`GWB_ACC`).

2000, 2009) measures land cover heterogeneity, or human influence, in a tri-polar classification of a location accounting for the relative contributions of the three land cover types agriculture, natural and developed in the area surrounding that location. The landscape mosaic is not restricted to use agriculture, natural and developed but can be applied to any three types of land cover. The heatmap summarizes the mosaic class occurrence frequency of all image pixels, which facilitates assessments of temporal changes and to compare different sites.

`GWB_MSPA` conducts the morphological spatial pattern analysis (Soille and Vogt 2009). MSPA analyzes shape and connectivity to segment the pixels of foreground objects in up to 25 feature classes. MSPA is a purely geometric analysis scheme, which can be applied to any thematic type of raster image.

`GWB_SPA` is a simpler version of `GWB_MSPA`. It conducts the simplified pattern analysis segmenting foreground patches into user-selectable 2, 3, 5 or 6 feature classes (see the Morphology product sheet accessible from the link in the section Supporting information). `GWB_SPA` describes the morphology of foreground objects for basic mapping and statistics, which may be sufficient for many application fields. Advanced analysis, more than 6 feature classes and including the detection of connecting pathways, require using the full version `GWB_MSPA`.

`GWB_P223` conducts a moving window analysis measuring the foreground density (P2), foreground contagion (P22) or foreground–background adjacency (P23) within the neighborhood that is centered on a subject foreground pixel (originally named Pf, Pff and Pfx in Riitters et al. 1997, 2002). P2 is the probability that a pixel in the neighborhood is foreground; P22 is the probability that a pixel next to a foreground pixel is also foreground; and P23 is the probability that a pixel next to a foreground pixel is a specific type of non-foreground pixel. Any `GWB_P223` analysis will be scale-dependent. The size of the moving window, which defines observation scale, can be set by the user in the module-specific file `p223-parameters.txt`. Foreground density (P2) forms the base for other derived analysis schemes, such as `GWB_LM/FAD/FRAG`. P22 and P23 describe the relative frequencies of different types of pixel adjacencies within a neighborhood. To illustrate the generic utility of this module, note that P2 provides the user with more flexibility to examine forest area density without the default choices of scales, thresholds and reporting formats of GWB_FAD and GWB_FRAG. The general interpretation of P2 with respect to fragmentation is straightforward – if there is no foreground fragmentation, then all foreground pixels meet all threshold FAD values at all observation scales. Fragmentation is therefore relative to a baseline corresponding to an 'all foreground' condition and deviations from that 100 percent baseline arise from natural (or endemic) fragmentation as well as anthropogenic fragmentation, which can be investigated further by using P22 and P23 to describe foreground edge typology within the same neighborhoods (Riitters et al. 2012, Riitters and Robertson 2021).

`GWB_PARC` conducts the parcellation analysis, resulting in a statistical summary file with details for each unique thematic class found in the image as well as the full image content: class value, total number of objects, total area, degree of parcellation. Parcellation, or the degree of dissection, may be useful to provide a quick tabular summary for each land cover class and the entire image. Together with the degree of division, it may be used to infer the dissection of a particular thematic class.

`GWB_RSS` conducts the restoration status summary analysis, a succinct summary of key network status attributes including area, extent, patch summary statistics, equivalent connected area (Saura et al. 2011) and degree of network coherence. As a normalized index, coherence can be used to directly compare the integrity of different networks or to quantitatively assess changes in network integrity over time. This feature may be useful to set priorities for restoration planning or to measure implementation progress and overall success of policy regulations.

`GWB_REC` conducts recoding of categorical image classes within the range of [0, 255] byte. Class values that are not encountered in the image will be skipped. Recoding may be useful to quickly setup appropriate input images for other GWB modules. For example, a land cover map could be recoded into a forest map by reassigning specific land cover classes to forest (2-byte – foreground), other land cover classes to background (1-byte) or to missing data (0-byte) to exclude those classes from a given analysis.

Implementation examples

Developed by the Food and Agriculture Organization of the United Nations (FAO), SEPAL (<https://sepal.io>) helps countries monitor and report on forests and land use. SEPAL offers users access to satellite data, with an easy-to-use interface, powered by cloud-based super computers, paving the way for improved climate change mitigation plans and data-driven land-use policies. Around the world, SEPAL is used to detect forest degradation, deforestation and monitor ecosystem restoration efforts. SEPAL provides free access to a variety of tools for geospatial analysis in a browser-based online portal. An introduction to using SEPAL is available at (<https://docs.sepal.io/en/latest/setup/index.html>).

GWB is available on SEPAL via the command-line interface (<https://docs.sepal.io/en/latest/cli/gwb.html>) as well as a GUI (Fig. 2, <https://docs.sepal.io/en/latest/modules/dwn/gwb.html>, <https://github.com/12rambau/gwb>). Here, the user can adapt any byte-formatted GeoTIFF input image and select dropdown and text-field entries to provide the GWB module-specific parameter settings. The results of the processed input images are stored in the user's home account directory under `~/modules_results/gwb/<module_name>/`.

In the SEPAL platform, the GWB modules are used to streamline approaches to assess degradation of forest edges (Shapiro et al. 2016, Vieilledent et al. 2018). Forest

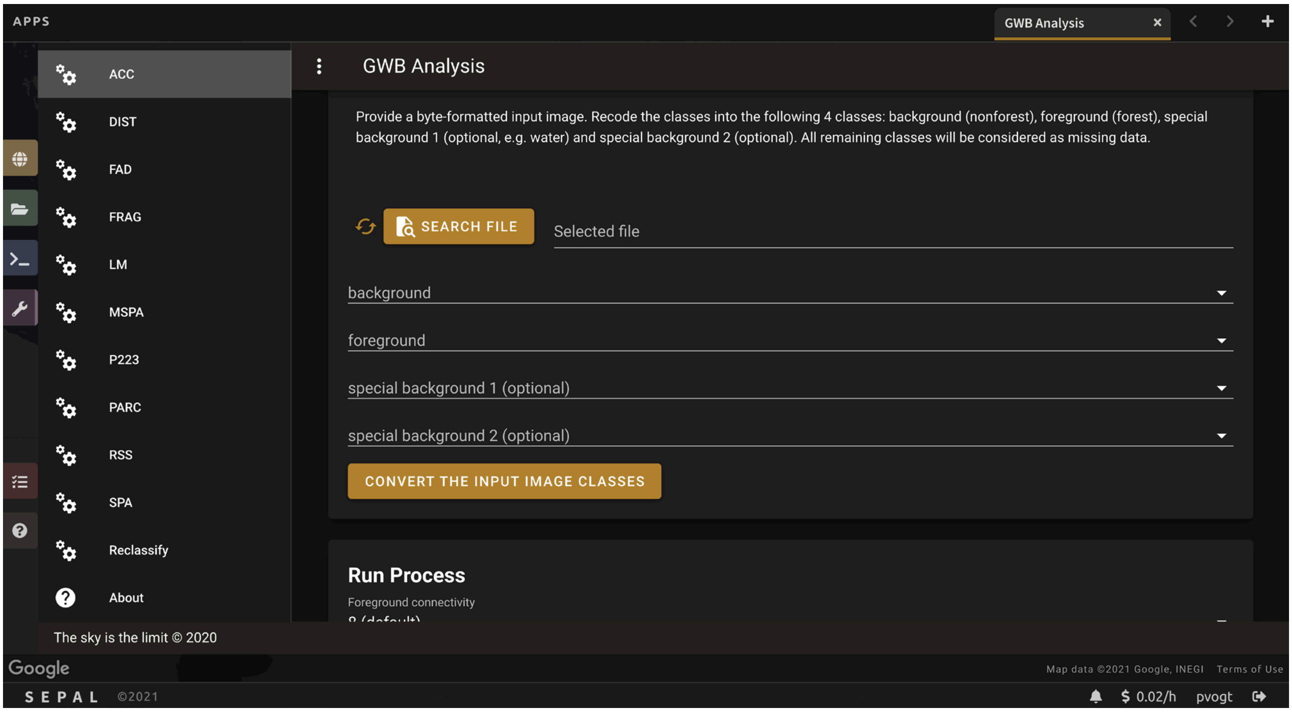

Figure 2. The GWB SEPAL user interface, showing a section of the accounting (`GWB_ACC`) module.

intactness and ecological integrity are common indicators of the conservation value of forest landscapes. The metrics provided by GWB through SEPAL represent easily accessible tools to measure the degree of intactness. The modules can be used in different thematic areas: as structural inputs relating to the drivers of deforestation and degradation, the relationship between forest disturbance and zoonotic disease spillover (Power and Mitchell 2004, Ellwanger and Chies 2021), disease spread (Diuk-Wasser et al. 2020) or as a proxy for high conservation value and high carbon stock definitions of forests (Jennings et al. 2003, Rietbergen-McCracken et al. 2007, Areendran et al. 2020).

Likewise, GWB is installed on the JRC Big Data Analytics Platform JEODPP (<https://jeodpp.jrc.ec.europa.eu/home/>, Soille et al. 2018), and on dedicated PCs of the EC-JRC and the USDA Forest Service, where it is used for satellite data analysis, contributing to national reporting in the RPA assessment (<www.fs.fed.us/research/rpa/>, Riitters 2011), the Brazilian agricultural research corporation Embrapa (Rosot et al. 2020) and the European Commission MAES reports (Maes et al. 2020). Euclidean Distance maps of forest patches were used to map and summarize forest fragmentation (Kozak et al. 2018). MSPA has been used in numerous peer-reviewed publications to map and summarize the spatial pattern, fragmentation and connectivity of forest and other land cover patches, including the detection of structural and functional connecting pathways, analyzing urban greenspace, landscape restoration up to classifying zooplankton species (MSPA website: <https://forest.jrc.ec.europa.eu/en/activities/lpa/mspa/>). Dedicated applications demonstrate interpretation of fragmentation (`GWB_FAD`) results and integration of GWB output with forest plot data (Riitters et al. 2012). Recent applications used advanced features in GWB to map and summarize the degree of forest fragmentation in the State of the World's Forest report (FAO and UNEP 2020, page 28–32) and the State of Europe's Forests 2020 report (FOREST EUROPE 2020, page 133–135) with additional technical details in the respective JRC Technical Reports for FAO (Vogt et al. 2019a) and Forest Europe (Vogt et al. 2019b).

Discussion

The scope of GWB is to facilitate the geolocation and statistical summary of specific spatial information contained in digital raster data. The command-line setup permits unsupervised, automatic batch-processing of multiple input images. All GWB modules are designed to result in a thematic reference base (Vogt 2019), following three principles:

1) *Spatial information* – answering the question: *Where*?
   Providing spatially explicit information is crucial to illustrate spatial variability, find hotspots and locate temporal changes. Only a map product allows for spatial planning and monitoring progress at selected sites. While a statistical summary can always be derived from a spatial map product, the inverse is not possible.
2) *Quantitative measures* – answering the question: *How much*?
   The analysis should result in clear and intuitive indicators, which is key for effective communication. Ideally, the indicators should be normalized, which further facilitates

the interpretation of a status indicator and its change over time. For example, the statement 'the situation has improved' is merely subjective, while the statement 'the degree has changed from 75% to 78%' provides a clear and unambiguous message.

3) *Generic and flexible analysis framework* – answering the question: *How*?

   A generic reference base can be equally derived for different thematic layers as well as at various spatial scales. In contrast to a case-specific end-product, a generic reference base functions as an intermediate framework, which the expert/end-user can then interpret for the individual application. Flexibility within a given thematic assessment is crucial to address individual user needs. Here, the expert can fine-tune the module-specific parameters to customize the analysis to best match the desired information of interest. For example, spatial patterns from the MSPA module can be reported from 2 to 25 classes depending on the desired detail or morphometric feature class of interest. The same is true for fragmentation, providing the full range in [0, 100] %, or a variety of categories and the choice of a per-pixel or patch-averaged reporting scheme.

The objective of this software note is to provide an introductory explanation of GWB and to stimulate user interest. Because GWB is a subset of the interactive desktop application GTB, the GWB results can be further investigated or processed in GTB or any other GIS-application.

The technically interested user may study the individual processing steps in the respective plain text IDL source code scripts. Users having access to an IDL development environment can easily compile amended module versions, or else reprogram the IDL source code in the programing language of their choice. IDL was chosen for personal programming preference and to take advantage of the very efficient IDL array processing libraries including multithreading capabilities. An additional benefit is that the IDL framework allows setup as an autonomous application package, independent of the underlaying Linux system libraries, thus avoiding the highly variable library dependencies across the multitude of Linux distributions.

Summary

Following the narrative of a thematic reference base, the individual GWB modules provide insights into various aspects of spatial attributes of land cover parcels of interest, but applications are equally valuable for input maps that portray attributes other than land cover. The combination of spatially explicit maps, normalized thematic indicators and a flexible reporting scheme results in a generic assessment framework. Intuitive indicators and geospatial information are key for effective policy design, project planning and quantitative reporting on ecosystem status and temporal trends. The flexible and harmonized reporting scheme can serve as a common framework to interpret land cover information for various endpoints in society and popular science, spatial ecology, resource management, land use planning, risk assessment and environmental monitoring in general. A reference data set on spatial information may also be intersected with other GIS data layers to enhance interpretation focusing on the assessment of environmental impacts triggered by urban sprawl, climate change, increased demand of bioenergy and land cover conversion.

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

Vogt, P. et al. 2022. GuidosToolbox Workbench: spatial analysis of raster maps for ecological applications. – Ecography 2022: 1–7 (ver. 1.0).

Acknowledgements – GWB includes research products designed and developed within the context of the Collaborative Research Arrangement between the United States Dept of Agriculture, United States Forest Service (Forest Service Agreement o. 14-MU-11330110-001) and the Joint Research Centre of the European Commission (Collaborative Research Arrangement No. JRC 33385). A big thank you to Bill Reynolds for providing deep insights into the world of Linux and application packaging. We thank two anonymous reviewers for the very helpful and constructive comments. The views expressed in this publication are those of the author(s) and do not necessarily reflect the views or policies of the Food and Agriculture Organization of the United Nations.

Author contributions

Peter Vogt: Conceptualization (lead); Methodology (lead); Software (lead); Writing – original draft (lead). **Kurt Riitters**: Conceptualization (equal); Methodology (equal); Software (supporting); Writing – original draft (equal). **Pierrick Rambaud**: Conceptualization (supporting); Software (supporting); Writing – original draft (supporting). **Rémi d'Annunzio**: Software (supporting); Writing – original draft (supporting). **Erik Lindquist**: Software (supporting); Writing – original draft (supporting). **Anssi Pekkarinen**: Writing – original draft (supporting).

Transparent Peer Review

The peer review history for this article is available at <https://publons.com/publon/10.1111/ecog.05864>.

Data availability statement

This article contains no original data..

Supporting information

The GTB product sheets provide further information and application examples of the GWB modules illustrated here. Accompanied by an overview presentation and extensive educational workshop material for ecological applications, UpToDate versions are available at: (<https://forest.jrc.ec.europa.eu/en/activities/lpa/gtb/#Productsheets>).

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