ESIS/Imalys software package: A tool for quantifying raster and vector-based landscape pattern and traits indicators from remote sensing data

Peter Selsam[1], Angela Lausch[2/3/4], Thilo Wellmann[4], Ronny Gey [1/5], Erik Borg[6/7], Jan Bumberger[1/5/8]

1 Department Monitoring and Exploration Technologies, Helmholtz Centre for Environmental Research GmbH – UFZ, Permoserstraße 15, 04318 Leipzig, Germany, peter.selsam@ufz.de, jan.bumberger@ufz.de

2 Department of Computational Landscape Ecology, Helmholtz Centre for Environmental Research - UFZ, Permoserstr. 15, D-04318 Leipzig, Germany; angela.lausch@ufz.de

3 Department of Physical Geography and Geoecology, Martin Luther University Halle-Wittenberg, Von-Seckendorff-Platz 4, D-06120 Halle, Germany

4 Humboldt Universität zu Berlin, Department of Geography, Landscape Ecology Lab, Unter den Linden 6, 10099 Berlin, Germany, thilo.wellmann@hu-berlin.de

5 Research Data Management-RDM, Helmholtz Centre for Environmental Research GmbH - UFZ, Permoserstraße 15, D-04318 Leipzig, Germany; ronny.gey@ufz.de

6 German Aerospace Center, German Remote Sensing Data Center, National Ground Segment, D-17235, Neustrelitz, Germany; erik.borg@dlr.de

7 University of Applied Sciences, Brodaer Str.2, D-17033 Neubrandenburg

8 German Centre for Integrative Biodiversity Research (iDiv) Halle-Jena-Leipzig, Puschstraße 4, D-04103 Leipzig, Germany

Abstract

Remote sensing has become an important tool and service for environmental research, especially for landscape analysis. Moreover, the spatial distribution and development of remotely sensed parameters can effectively complement and extend medical, biological, ecological and geographical tasks. However, data acquisition, data analysis and the selection of appropriate methods are still time-consuming. The ESIS (EcoSystem Integrity Service) project aims to establish environmental indicators on a well-defined and reproducible basis. The Imalys software library is designed to produce the indicators specified for ESIS as raster- and vector products from remote sensing data. These include various indicators of landscape diversity, boundaries, density of landscape elements and structures, and basic land cover types. All processes are sensor independent, scale invariant and applicable worldwide.

Keywords

Remote sensing, indicators, landscape patterns, ecosystem change, image segmentation

Metadata

Nr	Code metadata description	*Please fill in this column*
C1	Current code version	*Version 0.2*
C2	Permanent link to code/repository used for this code version	*https://github.com/c7sepe2/Imalys_ESIS-Software-Tools*
C3	Permanent link to reproducible capsule	*none*
C4	Legal code license	*GNU General Public License 3*
C5	Code versioning system used	*Semantic Versioning is the versioning system and git is the version control system used.*
C6	Software code languages, tools and services used	*Free Pascal 3.2.2*
C7	Compilation requirements, operating environments and dependencies	*Lazarus, Debian package 2.2.0+dfsg1-5ubuntu1 »https://www.lazarus-ide.org/«*
C8	If available, link to developer documentation/manual	*https://github.com/c7sepe2/Imalys_ESIS-Software-Tools/documents/manual/Index.md*
C9	Support email for questions	Peter.selsam@ufz.de

1. Motivation and significance

Climate change, land use intensity and urbanisation are driving rapid environmental change worldwide, with impacts ranging from the local to the global. In addition, landscapes, their processes and changes are complex and multidimensional. Therefore, complex multidimensional monitoring methods and approaches are needed to quantify, to model and better understand the causes and effects of drivers on the state and changes of ecosystem properties.

In recent decades, remote sensing (RS) has been increasingly applied operationally through the opening of RS data portals (e.g. Landsat mission, Copernicus mission) to record status and change, disturbances, processes and their interactions. This RS-based monitoring ranges from the monitoring of phylogenetic/genetic traits, structures and patterns, taxonomy and function of vegetation diversity [1–3], geodiversity [4,5], geomorphodiversity [6,7] or water quality [8] to landscape intensification and urbanisation [9–11]. This is based on the pixel reflections in an optical RS image, which are the integral and result of numerous complex interactions between light (the atmosphere) and the traits and trait variations and their interactions of the monitored land and water surface [5,12]. RS data capture traits and trait variation that exist at all scales, allowing RS to monitor traits and their variation on land cover and water surface at all spatio-temporal scales.

Currently, two operationally established approaches for quantifying and deriving structural, taxonomic and functional indicators based on RS data have been established. One is the patch matrix mosaic (PMM) modelling approach, where landscape metrics can be calculated from discrete RS data [13], the most well-known tool being Fragstats [14]. In addition, the gradient model (GM) approach is becoming increasingly popular, with landscape surface metrics derived from continuous RS data [15]. However, there is currently no tool for hybrid (raster and vector) quantification of structural, taxonomic or functional indicators from RS data in a hybrid RS tool to compensate for the disadvantages of one approach with the advantages of the other [13], and thus to better model and understand complex and multidimensional processes and changes.

Therefore, the motivation for the development of the Imalys tool is to fill this gap and create an RS tool that allows RS data processing, data management and continuous and discrete quantification of RS indicators in a hybrid tool. Furthermore, although RS has become a mature technology [16], it is still complex and difficult to use for practitioners from other disciplines. The ESIS/Imalys software package attempts to bridge this gap with defined features and open software solutions, and to provide an operational tool where environmental indicators can be quantified on a clearly defined and reproducible basis by the user.The ESIS/Imalis software library and tool is aimed at experts and non-experts in the field of RS and modelling by providing easy access to hybrid raster and vector indicator derivation and analysis. This paper provides an overview of the current state of the ESIS/Imalis software library and tool for quantifying raster and vector-based landscape patterns and feature indicators from RS data.

2. Software description

Imalys is a command line tool designed to extract landscape features (traits) from RS data. The process is fully automated and can be started with a single command. The software generates the required indicators by following a set of predefined modules that include all the necessary steps from compressed archives to the final product (see Figure 1) [17,18].

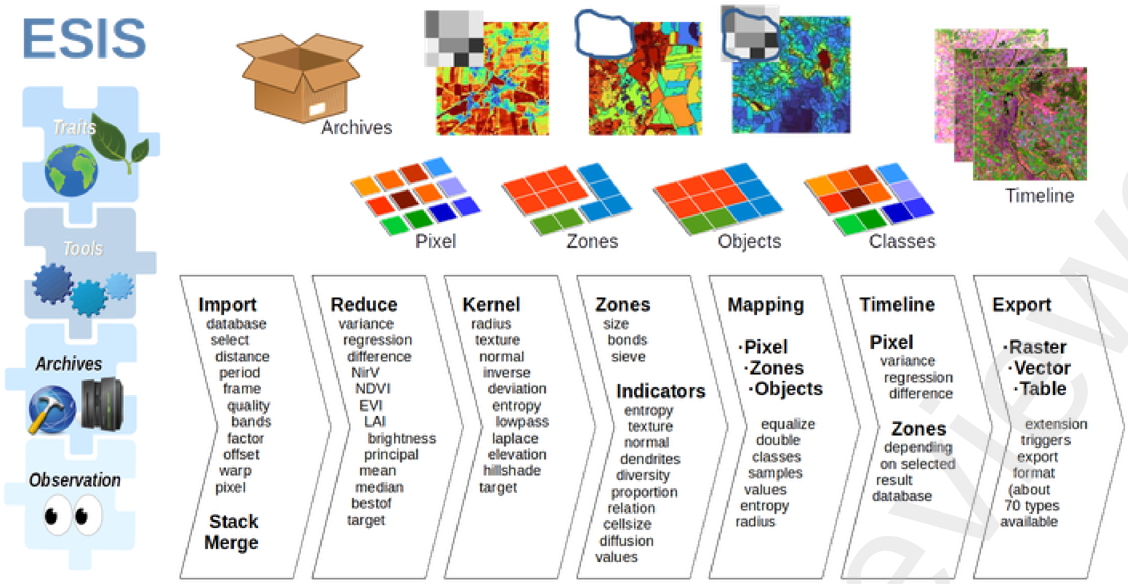


Figure 1: Imalys workflow: Modules to import specific regions (Import), extracting traits (Reduce, Kernel, Indicators), delineating local boundaries (Zones) or classifying landscape types (Mapping) can be combined into a seamless workflow. Once defined, the entire process can be executed and repeated without further interaction.

2.1 Modular design

Imalys is designed to run in a server environment such as that provided by the Open Source Geospatial Foundation [19]. However, the code and executables programs can also be used on any PC. Imalys is run on the command line using a shell or terminal. For ease of use, the entire process chain is provided as a text file (see Appendix B).

Most of the methods and analyses implemented in Imalys are also available in commercial software such as ERDAS [20] or ArcGis [21] and/or open source solutions such as QuantumGis [22]. The key to the Imalys concept was to bundle all the necessary commands and parameters into a single command that contains all the sub-steps and (depending on the application) only requires location, time and resulting indicators as inputs. On the other hand, the processes should be completely transparent and modifiable by the user without in-depth knowledge. All intermediate input and output products are compatible with each other, making it easy for the user to modify or add processes to a given process chain. Protocols for all sub-steps and error messages, which can also receive messages from external programs, allow complete control.

Imalys can repeat a given process chain with different input and output data or modified processes. Imalys solves this requirement by combining the “process chain” with names and parameters of all the necessary steps from RS data extraction to the final product and a "variable list” with varying parameters if necessary. Imalys automatically repeats the process chain for all the variable sets passed.

2.2 Indicators

Imalys supports standard pixel-oriented indicators for image analysis such as vegetation indices, kernel related processes and time series (Appendix D: Reduction, Kernel). For structural and quantitative landscape analysis, more specific indicators of landscape diversity such as shape, size and connectivity of delineated landscape structures (zones) were implemented (Appendix D: Zones, Features). Our aim was to find sub-areas with largely homogeneous characteristics [23], to analyze their spatial structure, connectivity and evolution, and to classify them.

Areas with largely identical characteristics are referred to below as "zones". Imalys uses the variance of neighboring pixels to separate zones from each other. The algorithm determines the boundaries between the zones in such a way that the variance of the pixels within the zones is minimized. Unlike approaches based on gradient descent or a watershed [24], the variance proved to be comparatively robust to noise and random fluctuations in the image data. Narrow or dendritic shapes such as watercourses or roads are mapped contiguously, even without clear boundaries.

2.3 Classes

Imalys implements processes to classify pixels, zones and spatial combinations of zones, which we call "objects". All classification processes are self-learning machine learning algorithms and do not require in-situ RS data for training. They extract characteristic combinations of feature in the image and return the accepted combinations as classes. The pixel-based classification (Appendix D: Mapping.Pixel) is based on the Euclidean distance in the N-dimensional spectral feature space. The range of values of the different features can be calibrated as required. Zone classification (Appendix D: Mapping.Zones) is very similar to the pixel-based classification, but can use the shape, size and connectivity of the zones together with the spectral RS information. Because classes are only assigned to whole zones, the classification is robust to statistical variations in pixel values in the image. There is no “salt and pepper" effect.

For object classes, the “fabric” process (Appendix D: Mapping.Fabric) searches for typical spatial patterns of different zones. Frequent combinations are classified as "objects". Objects are characterized only by the association of “their” zones, not by size, location or orientation. There is no limit to the size of an single object. On the other hand, large zones with unspecific neighbourhoods, such as lakes, farmland or industrial buildings can be classified as independent objects. For an internal test, we compared the results of an object classification of the Gohlis district in Leipzig based on airborne RS data with the rule-based classification [25]. Imalys does not reach the level of the rule-based classification, which itself distinguishes between building styles, but the result is immediately available and does not require any training. It can be used as an orientation for elementary land use types (see Figure 2).

Figure 2: Self-adaptive classification of the Gohlis district in Leipzig, Germany. 24 clusters formed by the Imalys process "fabric" method were combined into 13 classes (legend). The classification were based on aerial photographs and elevation model.

2.4 Documentation and Repository

The full source code, executable applications, developer and user manuals, notes on ongoing updates and documents on the background of the algorithms are published on GitLab [17] and GitHub [26]. A tutorial with raw data and examples for different applications and methods is available on Zenodo [18,27]. Appendix D shows the complete catalogue of commands and parameters that can be used to control Imalys and create process chains. The Imalys software is distributed under the GNU General Public License 3 [28]. Imalys makes extensive use of open source solutions and does not require any commercial licenses.

3 Illustrative examples

3.1 Time series and large areas

In order to provide adequate data for environmental health analyses and linkage to existing epidemiological cohorts [29], it is of interest to record the distribution and changes of green spaces at high spatial and temporal resolution for the whole of Germany over a period of 40 years. The process involves selecting spatially and temporally suitable RS data (Landsat 4-9) from any collection of provider's archives, checking the image quality within the passed frame, extracting the selected bands from the archives, calibrating the raw data for TOA reflectance, reprojecting all sections if necessary, combining sections from different tiles of the provider, generating a short time series of three months and forming a data product with the most frequent values for each pixel during the passed period. To keep the image data manageable we used the frames of the TK100 (Germany) [30] section for the final products. The resulting mosaic is the basis for all further products, in this case the vegetation indices NirV (see Figure 2) and NDVI (Appendix B).

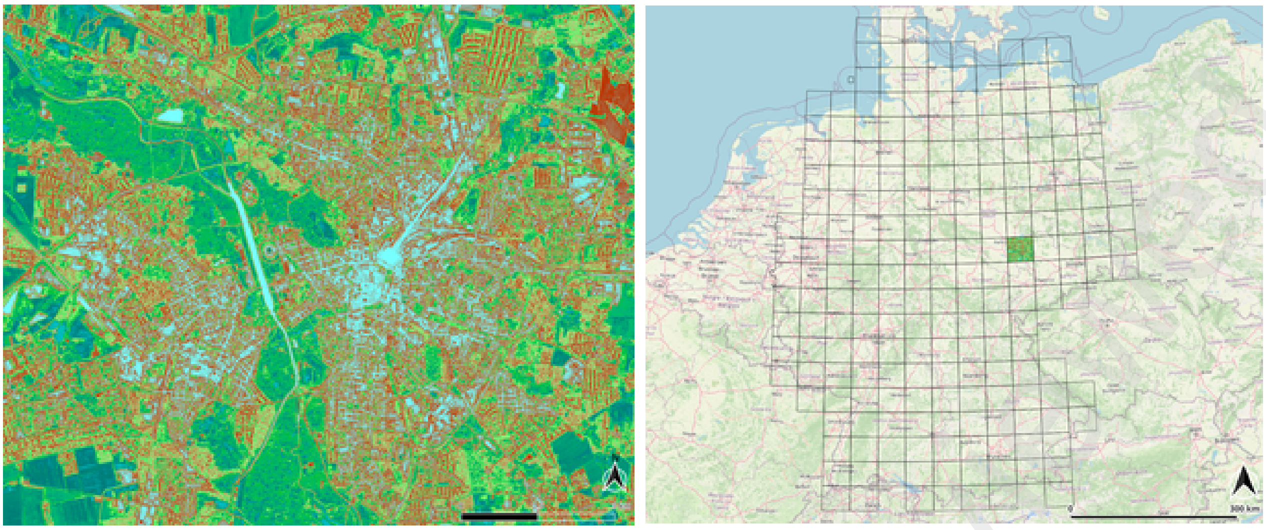


Figure 3: Left: Leipzig (Germany), vegetation index NirV, Sentinel-2 bands 4, 8, May to July 2018, values 0.0 ... 0.4, colours: ; **Right:** Distribution of map sheets in Germany, map sheet “c4738 Leipzig” is highlighted.

3.2 Diversity and landscape structure

Landscape diversity and the distribution and connectivity of the the delineated zones was a key issue in almost all of the above mentioned projects. A newly developed method was used to extract natural boundaries around areas with largely similar internal characteristics (zones). The average size of the zones can be selected. Indicators of the spectral characteristics of the zones can be derived from the mean pixel values. Figure 4 shows the degree of connectivity between zones measured using the "dendrites" indicator quantified with Sentinel-2 RS data for 2018. The zones are shown as thin black lines. In addition nine different indicators of the spatial density and the connectivity between the zones can be derived from the shape, size and contacts of the zones (Appendix D: Features).

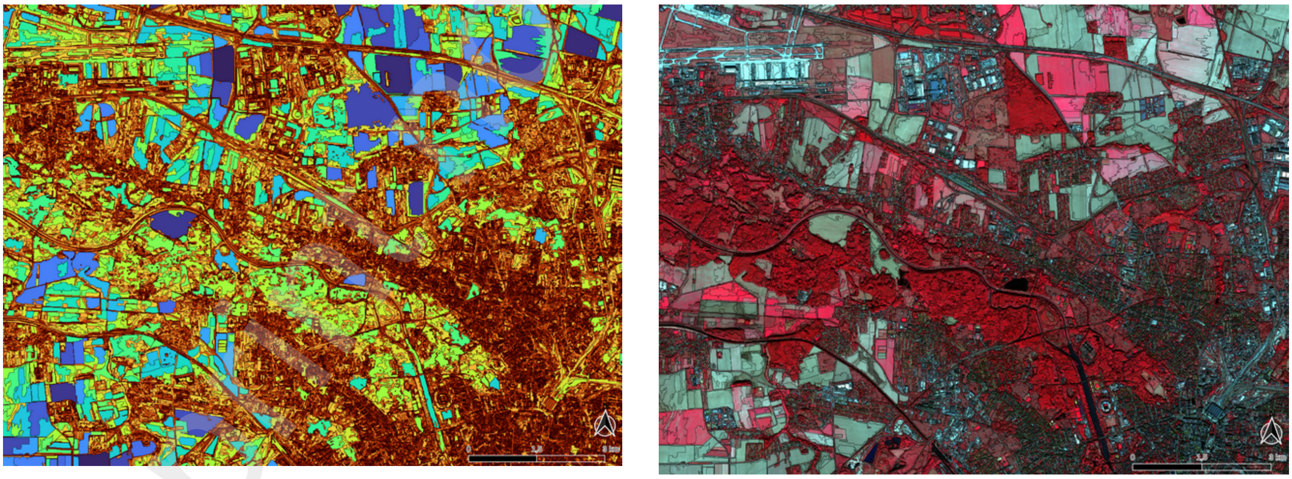


Figure 4: Left: Degree of connectivity between zones measured with the "dendrites" indicator, values 0.0...1.0, colors: ; **Right:** color infrared image, bands 8-4-3; **Both:** Northeast of Leipzig, Sentinel-2, 2018, zones marked as thin black lines.

3.3 Time series and change

Changes over time were the third parameter of great importance in almost all projects. Changes over time are easily recorded at pixel level using standard time series. Effort is required to obtain the data and to make the raw data from different sensors as identical as possible. For this task the time series are divided into a summer and an autumn period (May to July, August to October) covering several decades. The seasonal differences in Central Europe are larger than the differences between the years. The separation helps to better capture long-term variations accurately [31]. Figure 5 shows the change in the vegetation index NirV between 1994 and 2023 measured as a Gaussian regression for the Leipzig region.

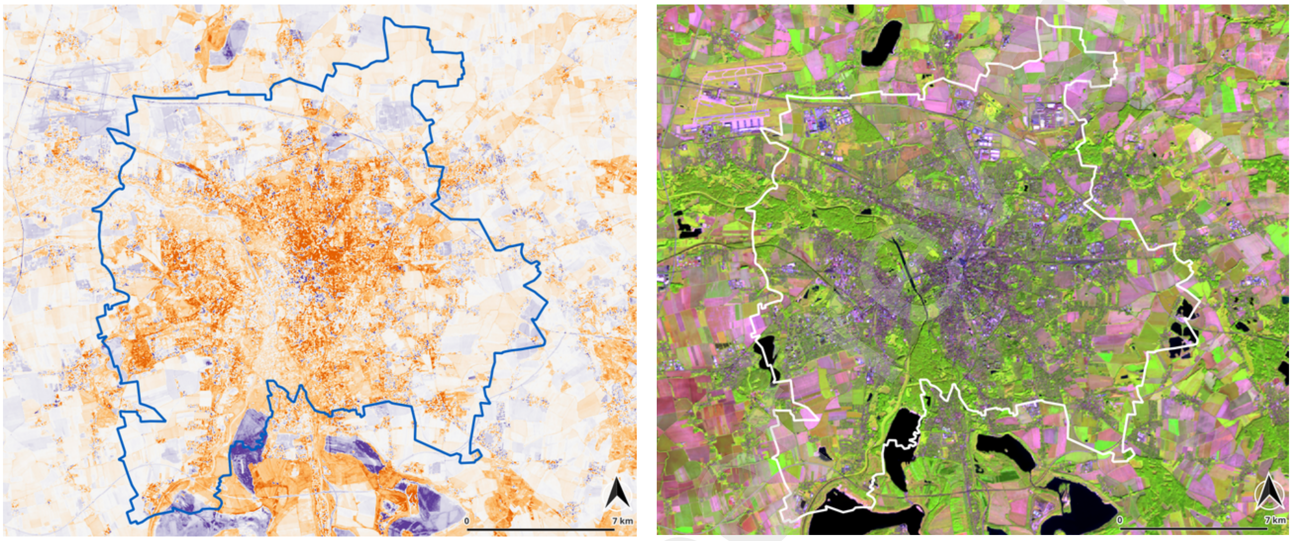


Figure 5: Left: Change in vegetation index NirV between 1994 and 2023, Leipzig region, Germany, measured as a Gaussian regression with regression values between -0.002 and +0.002, colours: .**Right:** Control image median 2018-2023, Landsat bands 5-4-3.

4. Impact

Imalys combines three main advantages: (1) flexible and modular design of own process chains by using interchangeable modules (2) new indicators for landscape structure, structural combinations and interactions of different landscapes (3) fully automated workflow for large amounts of data or numerous examples running on a PC. In this way, Imalys design for a continuous service.

4.1 Modular process design

Imalys can be used as a software library to extend own software solutions, but Imalys is also provided as a stand-alone executable software, controlled by a list of modules (named processes) and executed by a single command. All modules except the import of raw RS raster or vector data and the export and transformation to other file formats can be arranged, repeated and combined as required. Following the examples in the Imalys tutorial, own process chains can be created to solve specific needs or create new indicators simply by rearranging modules. Once designed, a process chain can be run as a stand-alone programme. Process chains can be shared via export and import functionality between users.

4.2 New indicators

Unlike pixels, zones differ in shape and size. Imalys defines indicators for both, spectral and morphological indicators. The average size of the zones can be freely chosen. Its value as an indicator is low. All other structural indicators therefore describe the relationships between the ratios the size of neighbouring zones or the length of the common boundaries (Appendix D: Features). Such indicators are largely independent of the scale and are easier to compare.

Some of the new indicators quantify the size, shape and connectivity of individual zones (Appendix D: Size, Dendrites). Others compare individual zones with their neighbours and provide diversity and connectivity between zones based on their morphology (Supplement D: Proportion, Relation) [6,7]. Analogous to the spectral diversity of pixels, the spectral diversity of zones is defined as an indicator (Appendix D: Diversity).

Zones also support pixel-based indicators that would normally be obtained with kernels (moving windows). Kernels always act as a low-pass filters. When zones are used as the window for calculating the indicators, the sharpness of the zones is maintained. Narrow watercourses that are barely more than a pixel wide, or finger-shaped road systems, will show a completely different combination of features than the surrounding area because only pixels from the same zone are used for the result. Zones support the analysis of changes and time periods. Zones can be derived from long RS time series. The boundaries then mark long-term boundaries of use, but also one-step changes. By comparing the spectral characteristics of neighbouring zones, periodic changes in use, such as different crops, can be distinguished from structural changes in the landscape.

4.3 Large periods and regions

Highly comparable optical information from space is available over four decades, and new sensor systems reduce the repetition periods to days while maintaining high ground resolution. We consider RS as a tool for documenting the distribution and change of natural resources and conditions in a precise and timely manner, e.g. in large cities [32] or over long periods of time [33]. Such analyses needs to be performed continuously and automatically. Imalys provieds easy-to-use tools to extract defined traits over long periods of time and large areas without constant manual interaction.

5. Conclusions

Imalys is a software package designed to process RS images as automatically as possible. Imalys is embedded in the ESIS concept to provide all the necessary tools to extract well-defined indicators from RS data based on pixels and on largely homogeneous areas (zones).

Imalys combines two functions, standard image processing and new landscape indicators based on largely homogeneous areas, into a single software package and a consistent set of commands. Imalys can process large and numerous areas without the need for intermediate steps or manual interaction. In addition, Imalys provides new indicators of landscape patterns, structure, diversity and spatial connectivity between different areas.

Acknowledgements

Parts of the work were funded by the German Federal Ministry of Digital Affairs and Transport (BMDV, grant no. 45KI19D041, Artificial Intelligence and Mobility - AIAMO project). We would also like to thank the Helmholtz Association and the Federal Ministry of Education and Research (BMBF) for supporting the DataHub initiative of the Research Field Earth and Environment. The DataHub enables an overarching and comprehensive research data management according to the FAIR principles for all topics of the programme Changing Earth - Sustaining our Future.

References

1. Rocchini, D.; Santos, M.J.; Ustin, S.L.; Féret, J.; Asner, G.P.; Beierkuhnlein, C.; Dalponte, M.; Feilhauer, H.; Foody, G.M.; Geller, G.N.; et al. The Spectral Species Concept in Living Color. *J. Geophys. Res. Biogeosciences* **2022**, *127*, 1–13.
2. Cavender-Bares, J.; Gamon, J.A.; Townsend, P.A. *Remote Sensing of Plant Biodiversity*; Cavender-Bares, J., Gamon, J.A., Townsend, P.A., Eds.; Springer International Publishing: Cham, 2020; ISBN 978-3-030-33156-6.
3. Lausch, A.; Erasmi, S.; King, D.; Magdon, P.; Heurich, M. Understanding Forest Health with Remote Sensing -Part I—A Review of Spectral Traits, Processes and Remote-Sensing Characteristics. *Remote Sens.* **2016**, *8*, 1029.
4. Zarnetske, P.; Read, Q.; Record, S.; Gaddis, K.; Pau, S.; Hobi, M.; Malone, S.; Costanza, J.; Dahlin, K.; Latimer, A.; et al. Towards connecting biodiversity and geodiversity across scales with satellite remote sensing. *Glob. Ecol. Biogeogr.* **2019**, *28*, 548–556.
5. Lausch, A.; Selsam, P.; Pause, M.; Bumberger, J. Monitoring vegetation- and geodiversity with remote sensing and traits. *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.* **2024**, *382*.
6. Lausch, A.; Schaepman, M.E.; Skidmore, A.K.; Truckenbrodt, S.C.; Hacker, J.M.; Baade, J.; Bannehr, L.; Borg, E.; Bumberger, J.; Dietrich, P.; et al. Linking the Remote Sensing of Geodiversity and Traits Relevant to Biodiversity—Part II: Geomorphology, Terrain and Surfaces. *Remote Sens.* **2020**, *12*, 3690.
7. Lausch, A.; Schaepman, M.E.; Skidmore, A.K.; Catana, E.; Bannehr, L.; Bastian, O.; Borg, E.; Bumberger, J.; Dietrich, P.; Glässer, C.; et al. Remote Sensing of Geomorphodiversity Linked to Biodiversity—Part III: Traits, Processes and Remote Sensing Characteristics. *Remote Sens.* **2022**, *14*, 2279.
8. Amani, M.; Mehravar, S.; Asiyabi, R.M.; Moghimi, A.; Ghorbanian, A.; Ahmadi, S.A.; Ebrahimy, H.; Moghaddam, S.H.A.; Naboureh, A.; Ranjgar, B.; et al. Ocean Remote Sensing Techniques and Applications: A Review (Part II). *Water* **2022**, *14*, 3401.
9. Kussul, N.; Lavreniuk, M.; Skakun, S.; Shelestov, A. Deep Learning

Classification of Land Cover and Crop Types Using Remote Sensing Data. *IEEE Geosci. Remote Sens. Lett.* **2017**, *14*, 778–782.

10. Wellmann, T.; Haase, D.; Knapp, S.; Salbach, C.; Selsam, P.; Lausch, A. Urban land use intensity assessment: The potential of spatio-temporal spectral traits with remote sensing. *Ecol. Indic.* **2018**, *85*, 190–203.
11. Xie, C.; Wang, J.; Haase, D.; Wellmann, T.; Lausch, A. Measuring spatio-temporal heterogeneity and interior characteristics of green spaces in urban neighborhoods: A new approach using gray level co-occurrence matrix. *Sci. Total Environ.* **2023**, *855*, 158608.
12. Le Provost, G.; Thiele, J.; Westphal, C.; Penone, C.; Allan, E.; Neyret, M.; van der Plas, F.; Ayasse, M.; Bardgett, R.D.; Birkhofer, K.; et al. Contrasting responses of above- and belowground diversity to multiple components of land-use intensity. *Nat. Commun.* **2021**, *12*, 3918.
13. Lausch, A.; Blaschke, T.; Haase, D.; Herzog, F.; Syrbe, R.-U.; Tischendorf, L.; Walz, U. Understanding and quantifying landscape structure – A review on relevant process characteristics, data models and landscape metrics. *Ecol. Modell.* **2015**, *295*, 31–41.
14. McGarigal, K.; Marks, B.J. *FRAGSTATS: spatial pattern analysis program for quantifying landscape structure.*; 1995;
15. McGarigal, K.; Cushman, S.A. The gradient concept of landscape structure. In *Issues and perspectives in landscape ecology*; Cambridge Univ. Press: Cambridge, 2005; pp. 112–119.
16. Jakimow, B.; van der Linden, S.; Thiel, F.; Frantz, D.; Hostert, P. Visualizing and labeling dense multi-sensor earth observation time series: The EO Time Series Viewer. *Environ. Model. Softw.* **2020**, *125*, 104631.
17. Selsam, P.; Lausch, A.; Bumberger, J. EcoSystem Integrity Service – Remote Sensing Software Library (Imalys), https://doi.org/10.5281/zenodo.7189794 (date:2022-12-31). *Zenodo* **2022**.
18. Selsam, P.; Bumberger, J.; Wellmann, T.; Pause, M.; Gey, R.; Borg, E.; Lausch, A. Ecosystem Integrity Remote Sensing—Modelling and Service Tool—ESIS/Imalys. *Remote Sens.* **2024**, *16*, 1139.
19. *OSGEO: https://www.osgeo.org/ (Status: 17.04.2024)*; 2024;
20. *ERDAS: https://hexagon.com/products/erdas-imagine (Status: 17.04.2024)*; 2024;
21. *ARCGIS: https://www.esri.com/en-us/arcgis/about-arcgis/overview (Status: 17.04.2024)*; 2024;
22. *QGIS: QGIS: https://qgis.org/en/site/ (Status: 17.04.2024)*; 2024;
23. Blaschke, T. Object based image analysis for remote sensing. *ISPRS J. Photogramm. Remote Sens.* **2010**, *65*, 2–16.
24. *eCognition:https://geospatial.trimble.com/en/products/software/trimble-ecognition (Status:17.04.2024)*; 2024;
25. Elze, S.; Banzhaf, E. High-precision monitoring of urban structures to understand changes in multiple ecosystem services. *Urban For. Urban*

Green. **2022**, *73*, 127616.

26. *Github: https://github.com/c7sepe2/Imalys_ESIS-Software-Tools (Status: 17.04.2024)*; 2024;
27. Selsam, P.; Gey, R.; Lausch, A.; Bumberger, J. Imalys - Image Analysis (0.1). *Zenodo* **2023**.
28. *GNU3: https://www.gnu.org/licenses/gpl-3.0.html (Status: 17.04.2024)*; 2024;
29. Heinrich, J.; Brüske, I.; Cramer, C.; Hoffmann, U.; Schnappinger, M.; Schaaf, B.; Berg, A. von; Berdel, D.; Krämer, U.; Lehmann, I.; et al. GINIplus and LISAplus. Design and selected results of two German birth cohorts about natural course of atopic diseases and its determinants. *Allergol. Sel.* **2017**, *1*, 85–95.
30. Blattschnitt der Topographischen Karte 1:100 000 (TK100) http://gdz.bkg.bund.de/index.php/default/blattschnitt-der-topographischen-karte-1-100-000-tk100-b100.html (Status: 17.04.2024). **2024**.
31. Linscheid, N.; Estupinan-Suarez, L.M.; Brenning, A.; Carvalhais, N.; Cremer, F.; Gans, F.; Rammig, A.; Reichstein, M.; Sierra, C.A.; Mahecha, M.D. Towards a global understanding of vegetation–climate dynamics at multiple timescales. *Biogeosciences* **2020**, *17*, 945–962.
32. Wellmann, T.; Andersson, E.; Knapp, S.; Lausch, A.; Palliwoda, J.; Priess, J.; Scheuer, S.; Haase, D. Reinforcing nature-based solutions through tools providing social-ecological-technological integration. *Ambio* **2023**, *52*, 489–507.
33. Wellmann, T.; Schug, F.; Haase, D.; Pflugmacher, D.; van der Linden, S. Green growth? On the relation between population density, land use and vegetation cover fractions in a city using a 30-years Landsat time series. *Landsc. Urban Plan.* **2020**, *202*, 103857.
34. Badgley, G.; Field, C.B.; Berry, J.A. Canopy near-infrared reflectance and terrestrial photosynthesis. *Sci. Adv.* **2017**, *3*, 1–6.

Appendix A: Imalys commands

Imalys has a large number of commands and parameters for developers due to the variety required. Commands summarize basic functions, parameters select processes and accept inputs. The following commands are currently implemented:

Home	Select a working directory and define paths for protocols.
Catalog	Create a database with the position and acquisition times of archived image data
Import	Extract images from archives, project them onto a selected frame, calibrate the values and combine tiles from different archives.
Compile	Combine, transform and check imported images as input data for all further commands.
Reduce	Combine or compare pixels in different bands, create indices, analyze time series and return principal components.
Kernel	Combine pixels from the local neighborhood of each pixel to new values, change contrast and filter edges
Zones	Creates a seamless network of image partitions (zones) with largely identical characteristics
Features	Determine spectral and morphological characteristics of the zones and save them as attributes
Mapping	Classify pixels, zones or spatial patterns of zones (objects)
Compare	Compare classes with references
Export	Transform processing results into another image format. Zones and classes can also be exported in vector format.
Replace	Change variables in a process chain. Structurally identical processes can be repeated automatically with different commands and parameters.

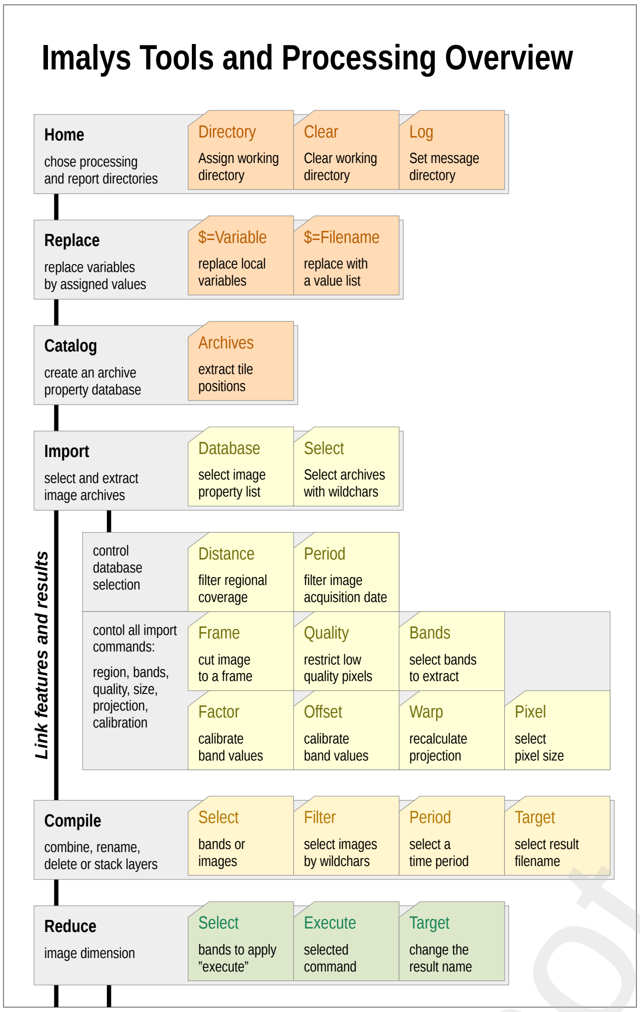
Appendix B: Process Chain Example

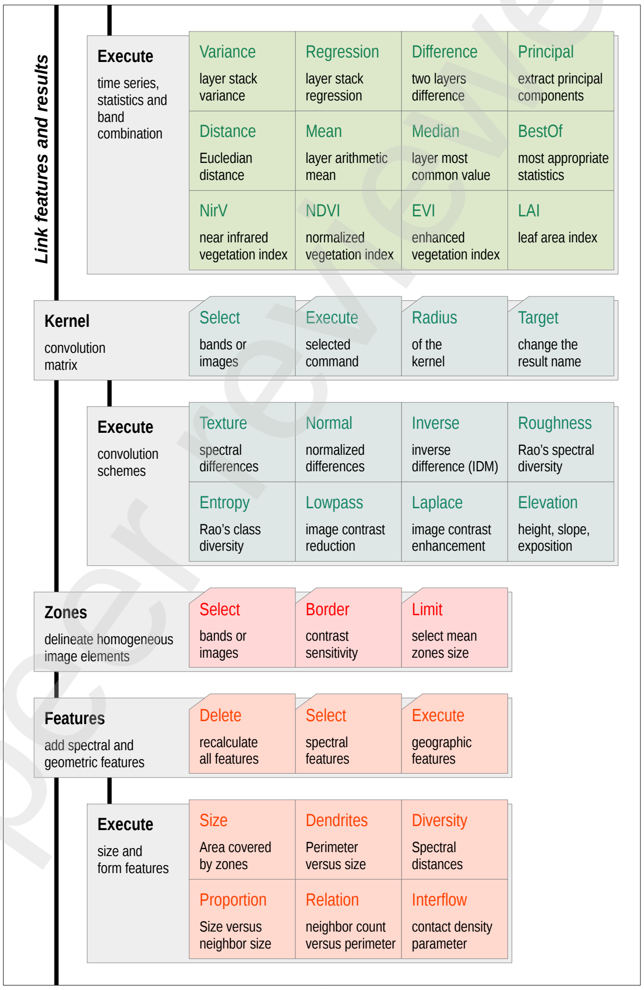
Appendix B shows how a specified region (frame) is extracted from each collection of compressed USGS Landsat 8/9 archives. The result is a seamless composition of all images taken from August to October 2013 with the OLI bands 2…7, calibrated to TOA reflectance and projected to UTM, WGS-84, Zone 32.

```
IMALYS [import seasonal image]

home
      directory=/home/»user«/.imalys
      clear=true
      log=/home/»user«/ESIS/c1114_Sylt

import
      database=/media/»user«/STOCK/Landsat-89/2023/center.csv
      distance=1.00
      frame=/home/»user«/ESIS/v_TK-100/c1114.gpkg
      quality=0.86
      period= 20230801-20231031
      bands=_B2, _B3, _B4, _B5, _B6, _B7
      factor=2.75e-5
      offset=-0.2
      cover=0.9
      warp=32632
      pixel=30

compile
      search=LC0*.hdr

reduce
      select=compile
      execute=bestof

export
      select=bestof
      target=/home/»user«/ESIS/c1114_Sylt_bestof_20230801-20231031.tif
```

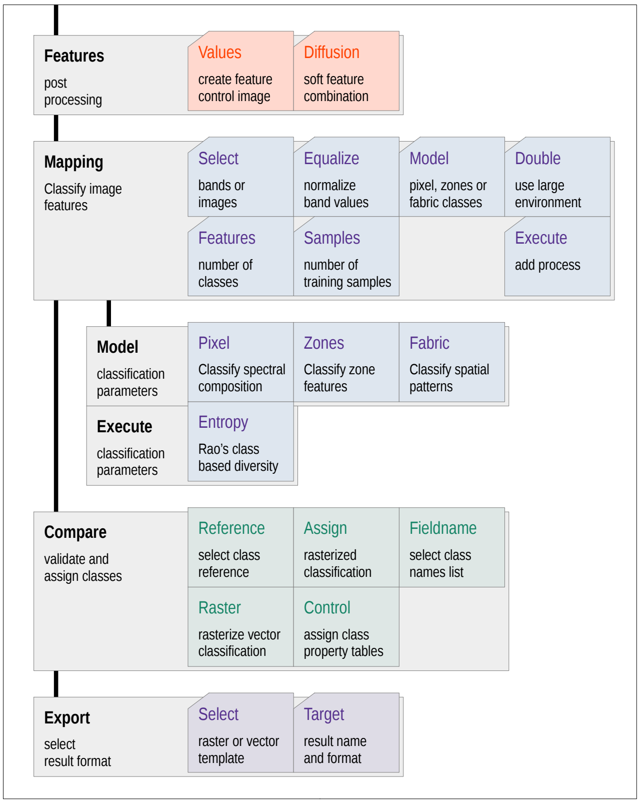
Appendix C: Commands and parameters overview

(as »https://github.com/c7sepe2/Imalys_ESIS-Software-Tools/documents/manual/Index.md«)





Appendix D: Commands definitions and examples



Appendix E: Functions, tools, descriptions and formulas. The following tables show tools and traits and their definitions by means of a text box and a formula. The indicator names also serve as commands in the Imalys process chain, as a file name of the process results, and as field names in tables. Therefore, the names are short and can have a much wider meaning in general usage. Imalys tools are aids to execute the process chain.

Spectral

Traits	Description	Formula
Variance	Variance based on standard deviation The “variance” command determines the variance of individual pixels based on a standard distribution for all of the bands in source. For multi-image stacks, “Variance” determines the variance for each band separately and gives the result as a multispectral image of the variances. The result can be further reduced to a one band image with the first principal component of all bands using “principal”.	$\frac{\sum_i v^2 - \left(\sum_i v\right)^2 / n}{n-1}$ v: values i: items n: item count

Regression	Regression based on standard deviation “Regression” returns the regression of individual pixels of all bands in source. “Regression” uses the temporal distance of the recordings from the metadata of the images. To do this, the images must have been imported with “extract” or have been dated afterwards with “extend”. Similar to “variance”, “regression” determines the regression for each band separately if multispectral images are provided and gives a multispectral regression.	$\frac{\sum_i t\cdot v-\sum_i t\sum_i v/n}{\sum_i v^2-(\sum_i v)^2/n}$ t: time v: values i: items n: item count
Difference	Euclidean distance of two n-dimensional properties “Difference” gives the difference between the values of two bands or two images. For multispectral images, “difference” generates a result for each band separately and returns a multispectral image of the differences for all bands.	$v_a - v_b$ v: pixel value
Vegetation	*Near-infrared vegetation index (NIRv)* The NIRv index is calculated as the product of near infrared radiation and the normalised difference of the red and the near-infrared radiation. The calculation follows the most common NDVI definition but shows better mapping in sparsely vegetated areas. Vegetation indices were introduced to estimate the plant-covered proportion of the landscape. The result depends on the photosynthetic activity of the plants. Vegetation indices try to quantify the photosynthetically active radiation (PAR) as a measure of plant metabolism. There are about 20 different approximations described [34].	$\frac{(N-R)}{(N+R)}\cdot N$ N: near-infrared value R: red band value Value range: 0…1
Principal	“Principal” gives the first principal component of all bands. The first principal component reflects the brightness or density of all image bands. Imalys uses this process as brightness in several other cases.	$\sqrt{\sum_i v_i^2}$ v: values i: items
Mean	Arithmetic mean, bands or images Mean gives the arithmetic mean of all image bands provided. For multispectral images, “mean” is individually calculated for each band. The process returns a multispectral image of mean values.	$\frac{\sum_i v_i}{n}$ v: values i: items n: item count
Median	*Most common value for each pixel from a stack of bands* “Median” reflects the most common value of each pixel in a stack of bands or images. For multiple image stacks, “median” is individually calculated for each band. Median will mask rare values. Image disturbances like clouds or smoke will be masked if more than half of all pixels show an unchanged value.	Value in the middle of a sorted value list.
Convolution		

Traits	Description	Formula
Texture		
Normal	*Normalised texture* “Normal” collects the first principal component of all normalised differences between two neighbouring pixels within a given kernel and returns the mean. Landscape diversity increases with texture. The normalised texture is independent of brightness or illumination (shadows). In contrast to Rao’s “entropy” or “roughness”, “normal” will return similar values for regular and randomly distributed patterns.	$\sqrt{\sum_b \left(\frac{v_i - v_j}{v_i + v_j}\right)^2}$ v_i: pixel value v_j: neighbour pixel value Value range: 0…1
Inverse	Inverse difference moment (IDM) “Inverse” creates a new image with the inverse difference moment (IDM) proposed by Haralik (Haralik 1979). “Inverse” is particularly high in dark regions and low in bright regions. It can complement “texture” and has proved useful in the analysis of settlement structures.	$\sqrt{\sum_b \frac{1}{(v_i - v_j)^2}}$ v: values I,j: neighbor pixels b: bands
Roughness (Rao’s Q Index)	*Rao‘s diversity based on pixels* As “Texture” does, Rao’s approach evaluates the spectral difference of individual pixels, but does not only compare neighbouring pixels, but all pixels within the kernel. Unlike the classical “texture” or “normal” indicators, “roughness” is insensitive for the spatial distribution of the pixels within the kernel. “Roughness” returns a measure for landscape diversity based on pixel differences within a given kernel. Most like “Entropy”, each distribution of a given set of pixels will produce the same result.	$\sum_{ij} (d_{ij} \cdot p_i \cdot p_j)$ d_{ij}: Density difference between pixel (i) and (j) p_i, p_j: Frequency of pixel values (I) and (j) Value range not limited
Entropy	*Rao‘s entropy (diversity) based on classes* “Entropy” collects the number of class differences and class similarities for all pixel combinations within a given kernel. The number of different class combination is scaled with the spectral differences between the classes. Entropy needs a classification of the images to run. The easiest way to obtain this classification is to call the “Mapping” trait. Alternatively, “Entropy” can use an existing classification. “Entropy” returns the diversity of landscape classes within a given kernel. “Entropy” ignores small landscape differences that are represented by the same class and returns a more abstract level. Rao’s approach is insensitive to the distribution of the pixels within the kernel. A chessboard-like distribution of two classes will produce the same result as two homogeneous areas with the same classes.	$\sum_{kl} (d_{kl} \cdot p_k \cdot p_l)$ d_{kl}: spectral Distance between the the classes (k) and (l) p_k: frequency of class (k) p_l: frequency of class (l) Value range not limited

Lowpass	Reduce local contrast "Lowpass" reduces the local contrast of the image data according to the selected "radius". The process reduces the local contrasts and can fix small bugs. "Lowpass" uses a kernel with a normalised Gaussian distribution. The kernel size can be selected freely. Imalys implements large kernels through an iterative process to significantly reduce the processing time.	$\sum_{ij}(v_{ij} \cdot k_{ij})$ v: image values k: kernel values I,j: kernel index
Laplace	Enhance local contrast A "Laplace" transformation (Mexican head function) enhances the image contrast and can make lines and closed shapes clearly visible. Imalys implements the transformation as the difference between two Gaussian distributions with a different radius. The parameters "inner" and "outer" control the size (kernel radius) of the two distributions.	$\sum_{ij}(v_{ij} \cdot (k_{ij} - g_{ij}))$ v: values k: inner kernel g: outer kernel I,j: kernel indices

Create Zones

Traits	**Description**	**Formula**
Zones	Delineated homogeneous image elements The "zones" process delineates a seamless network of zones that completely covers the image. The zones are assigned with the spectral signatures of the image data as attributes. The attributes can be expanded (below). "Zones" were introduced to provide a structural basis that can be used for landscape diversity and other structural features. Zones allow for easy transformation of raster images to a vector format like maps.	Structural delineation similar to an inverse watershed.
Dendrites	*Quotient of zone perimeter and zonal size* "Dendrites" returns the quotient between perimeter and size of single zones. Both values grow with larger zones, but the size grows faster. Large zones will show lower values than smaller ones with the same shape. "Dendrites" was introduced as a size-independent measure of spatial diversity. Long and small zones may be quite large but their role in landscape diversity is similar to that of small zones. Small, thin or dendritically shaped zones show high values, large compact zones show the lowest.	$V_r = \frac{p_z}{s_z}$ v_r: result value p_z: perimeter (zone) s_z: size (zone) Value range: 0…4

Diversity	Spectral diversity for all neighbour zones “Diversity” is calculated as the mean principal component of all spectral differences between all pixels of a single zone. This includes all pixel borders to neighbour zones and also all pixel borders within the zone. The differences are calculated with the zonal mean values, not with individual pixels. “Diversity” was introduced as size-dependent spectral diversity. The principal component intensifies the contrast of single bands. High values indicate small zones and high spectral differences. Small or narrow zones embedded in large zones are emphasized.	$\frac{\sqrt{\sum_n (v_i - v_n)^2}}{b_p}$ v_i: zonal value v_n: neighbour value b_p: pixel borders Value range: 0…1 for reflection values
Proportion	Size difference between central zone and all neighbours “Proportion” returns the relation between the size of a single zone and all its neighbours. The result is calculated as difference between the size of the central zone and the mean size of its neighbours. As the size is given on a logarithmic scale, the “mean” is not an arithmetic but a geometric mean. The result will be negative if the central zone is smaller than its neighbours. “Proportion” resembles a texture for zonal sizes. Proportion is independent of the individual size of a zone. Values around zero indicate equally sized neighbour zones. Zones with smaller neighbours show positive values; zones with larger neighbours are negative.	$\frac{\sum_j \ln(s_i) - \ln(s_j)}{n}$ s_i: size, central zone s_j: size, neighbour zone n: number of neighbours
Relation	Quotient of cell perimeter and number of neighbours “Relation” is calculated as the relation between the perimeter of the zone and the number of neighbouring zones. “Relation” was introduced as an indicator for spatial diversity. Large zones and small zones with few neighbours will have large values. Small zones with many neighbours will show higher values. Like “Dendrites”, “relation” also returns information about the shape and the connection of the zones. Zones with many connections may provide paths for animal travels and enhance diversity.	$R = \frac{p}{c}$ R: relation p: perimeter c: number of neighbours
Size	Size of one zone given as natural logarithm The zonal size is calculated from the sum of pixels covering the zone. Landscape diversity increases with smaller zones	$S = \ln(a)$ a: area of zone [ha]

Diffusion	Smooth properties in a zones network The algorithm for value equalisation in zones mimics diffusion through membranes (borders). In the process, features “migrate” into the neighbouring zone like soluble substances and combine with existing concentrations. The intensity of diffusion depends on the length of the common border and the number of iterations. The size of the zones does not matter. The process is only controlled by the number of iterations. Each iteration includes a new layer of contributing zones. The influence of distant zones on the central zone decreases with distance. Entries over 10 are still allowed, but rarely have a visible effect.	$\sum_{t}(a\cdot s)+\sum_{ij}(a_j\cdot b-a_i\cdot b)$ a: attribute s: zone size b: border length i,j: zone indices t: iterations (time)
External		
Values	Raster representation of a vector map with attributes “Values” creates a multiband raster image from vector borders and the attributes of the different polygons. “Values” mainly serves as a control feature.	Raster image from vector polygons

Classification

Trait/Tool	**Description**	**Process**
Pixel	“Pixel” classifies spectral combinations “Pixel” selects a pixel-oriented classification of the image data. The process uses all bands of the provided image. The process is controlled only by the number of classes in the result. All values should have a comparable value range, as calibrated images do.	Fully self-adjusting classification of all pixel values
Features	“Features” classifies spectral and spatial properties of zones “Features” selects the classification of zones based on their features. The process is controlled by the selected features and by the number of classes in the result. Each feature can be selected individually. As with “pixels”, the value range of the features should be comparable.	Fully self-adjusting classification of all zones’ features
Fabric (Objects)	“Fabric” creates and classifies image objects In this context, adjacent zones with an individual combination of different features are called objects. Object types (classes) and image objects are created during the same process. The object definition relays only on the borders between different types of zones. Thus, objects are characterized by their spatial pattern.	Fully self-adjusting delineation and classification of image objects based on zones with different features.
Compare	Compare a mapping with a reference Automated classification is driven by image features. Real classes are not necessarily defined by their appearance. “compare” allows for evaluating if and up to what degree real classes can be detected by image features.	Confusion matrix for false and true detection and denotation

Rank	Correlate distributions “Rank” calculates a correlation coefficient based on a rank correlation model after Spearman. A rank correlation is independent of the basic value distribution. Therefore, it can be used for each set of data.	$1-6\frac{\sum_i (r_i-s_i)^2}{n\cdot(n^2-1)}$ r,s: item rank i: item index n: item count

Export

Traits	**Description**	**Process**
Raster	Export values using an image raster format Images and processing results can be exported in 48 different raster formats (according to most recent gdal library). Raster export includes vector-based process results. Standard format is ENVI labelled.	gdal library
Vector	Export values using a vector format Vector-based results can be exported using 23 different vector formats (according to most recent gdal library). Vector export includes automated transformation for most of the raster data. Standard formats are ESRI Shape and CSV.	gdal library
Table	Export tables using a table format Value grids can be exported in different database and spreadsheet formats. Table export includes tables linked to raster or vector data. The standard format is CSV.	gdal library