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Research paper

ZonalMetrics - a Python toolbox for zonal landscape structure analysis

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ABSTRACT

We present a Python toolbox for the calculation of zonal landscape metrics. Instead of global calculations focusing on the whole landscape, the proposed ZonalMetrics toolbox allows the calculation of landscape metrics for user-defined zones. Such zones can be defined through regular units (e.g. hexagons, grids) that can be created within the toolbox. In addition, any polygonal set specified by the user (e.g. administrative units) can be used. The implemented set of landscape metrics is specifically selected and valid for calculations within zones. The tool is demonstrated based on a case study for the Warsaw metropolitan area and the possibilities of applying the toolbox for different zonal layers are illustrated. The implementation is based on the Python toolbox introduced in ArcGIS 10.1, offering an easy to use graphical user interface and batch calculation possibilities. The source code is free and open to the community and extendable to specific needs.

1. Introduction

Landscape metrics were originally developed to characterize landscape patterns in an ecological context (McGarigal and Marks, 1995). Nowadays their applications are continuously growing in this field, and operational applications related to regulation and information functions continue to emerge (Uuemaa et al., 2013).

The majority of approaches for the calculation of landscape metrics are computed for the overall study areas which are usually limited by the extent of administrative units or the available data. Some authors propose sampling as an alternative to whole study area calculation (for example Ramezani et al., 2009). Since first introduced by McGarigal and Marks (1995), the following levels of calculation are mainly used within such data extents: (1) whole landscape, (2) focus on classes, and (3) focus on single patches, which supported by many software packages or software plugins. The pioneer application was FRAGSTATS (McGarigal and Marks, 1995), a raster based standalone program offering the possibility to calculate a wide range of landscape metrics, and its development still continues today (McGarigal et al., 2012). These metrics or subsets were also implemented in other software packages such as the standalone programs APACK and IAN (Mladenoff and DeZonia, 2004) and plugins for ESRI's ArcGIS, e.g. Patch Analyst (Rempel et al., 2012).

A new possibility to calculate landscape metrics without the cumbersome and time-intensive data conversion between vector and raster data was introduced with the V-LATE extension for ArcGIS (Vector-based Landscape Analysis Tools, Lang and Tiede, 2003). This possibility of calculating landscape metrics using categorical vector layers seems to be prospective, especially since vector-based layers seem to dominate in the field of landscape-relevant data/data exchange. Also, new spatial information extraction methods such as Object-Based Image Analysis (OBIA), as opposed to pixel-based methods, are becoming increasingly popular and are evolving into a new paradigm in the field of geoinformation science (Blaschke et al., 2014), resulting in GIS-ready vector data layers instead of categorical raster layers.

Nowadays, the vector-based approach is also implemented in the open source landscape metrics library Land-metrics DIY (Zaragozí et al., 2012). Vector layers are also used as input in tools using metrics specialized for specific applications, such as Polyfrag (MacLean and Congalton, 2013), which computes fragmentation metrics for vector-based maps. Another example is Marxan (Watts et al., 2009), a decision support tool for conservation planning, where a nonstandard set of metrics is implemented. Patch Analyst (as of version 4) supports both kinds of data models (vector and raster) (Rempel et al., 2012).

The zonal level of the landscape metrics calculation, rather than the focus area defined by the data set, has so far only been implemented in a few tools. The latest version of Patch Analyst (Rempel et al., 2012) incorporates the functionality to calculate landscape metrics in a hexagonal grid. Marxan (Watts et al., 2009), a conservation planning software, allows to calculate certain planning support metrics within regular units and user-defined zones e.g. parcels or hydrological units.

Hassett et al. (2012) show (using FRAGSTATS) limitations of common tools designed for the calculation of landscape metrics. The

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authors divided the land cover dataset into statistical zones. This procedure may introduce a new bias to the results, caused by e.g. patches of small sizes and artificial borders of patches, which occur when larger patches are cut.

We propose the ZonalMetrics toolbox, a new open source tool with a specialized functionality for calculating landscape metrics on the zone level, which addresses the following needs:

- Direct analysis of user-defined vector based categorical (polygon) layers.
- A set of available landscape metrics tailored to calculations within any user-defined zones (for example regular gridded zones, administration zones, environmental zones).
- Additional functionalities, such as specific zone generation (pies, hexagons) for specific applications.
- The source code is free and open to the community and extendable to specific needs.

2. Theoretical background for ZonalMetrics toolbox

2.1. Statistical zones

The statistical zones used in our ZonalMetrics toolbox as the basis for the landscape metrics calculation are per definition freely selectable/integrable and generally divided into two main categories: regular tessellations and user-defined irregular ones. Both have advantages and limitations depending on the application case and metrics to be calculated, as will be discussed in the following paragraphs.

The main advantage of using regular sampling units is their equal area and perimeter, creating statistically similar units across the area being analyzed, and therefore providing a defensible statistical basis for sampling purposes (Bassett and Edwards, 2003; White et al., 1992). This is why regular sampling may sometimes show much better patterns and/or processes in the landscape compared to other predefined units.

The possible regular tessellations may be squares, hexagons, or triangles (Carr et al., 1992). While triangles are rarely used (Birch et al., 2007), regular square grids dominate in many applications. They are, for example, defined as a standard geographical grid in the European Union (INSPIRE, 2010). Hexagons are also rarely used but are recommended as a better alternative to other regular tessellations to be used as a statistical unit (cf. Birch et al., 2007; Carr et al., 1992; Jurasinski and Beierkuhnlein, 2006; Krebs, 1989; Rempel et al., 2003). The main advantages are (1) that any given point inside a hexagon is closer to the centre of that hexagon than any given point in an equal-area square or triangle would be and (2) hexagons are the only geometric shape for regular tessellations that shares a real border with every neighbor and not only a single point with some neighbors (as squares and triangles do).

The limitations of a zonal approach for calculating landscape metrics are especially important when regular tessellations are employed (Hassett et al., 2011; Hunsaker et al., 1994; Klein et al., 2009; O'Neill et al., 1996; Vuilleumier and Metzger, 2006). The following considerations have to be taken into account if a zonal approach is selected for a landscape analysis:

- The borders of regular zones do not capture real environmental units.
- The definition of zones predefines the scale of analysis, which has to be taken into account since each phenomenon to be analyzed may have a specific scale domain (see Levin, 1992; Turner et al., 1989; Wiens, 1989).
- The sensitivity of the selected metrics to the extent of the analysis is important, especially for an artificially limited extent of statistical zones.
- A patch truncation effect leads to larger patches being cut by the borders of statistical zones. Above all, this limitation concerns linearly elongated objects or those that are much larger than the others, and means that their shape and other characteristics may not be captured. Artefacts resulting from such cut-offs may cause underestimation of the value of some metrics (e.g. Mean Patch Size MPS) and overestimation of others (e.g. Patch Density PD).
- The potential introduction of artificial patch edges when the analysis is performed by simply cutting the analyzed layer with statistical zones.

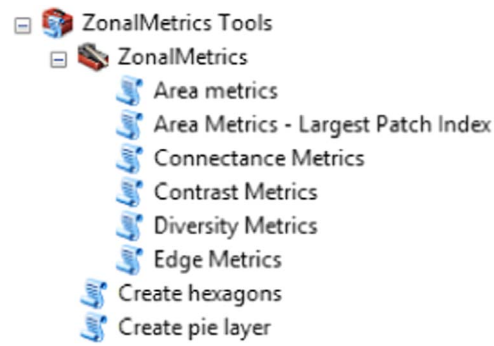

Fig. 1. Main components of the ZonalMetrics toolbox.

The same problems may to some degree also occur when administrative units are used that are delineated according to human management priorities and take no ecological units into consideration (Bassett and Edwards, 2003). Nevertheless, administrative units usually cover a large area so they may contain a representative part of the landscape. Despite the weaknesses, analyses per administrative unit are often needed for regional or local planning purposes. Furthermore, they fit better into existing data structures provided by the national repositories (reporting duties) and are therefore often requested in such extents.

Zones delimited according to ecological criteria, such as landscape or ecological units and watersheds, are recommended against other zones because they offer the potential to increase the sensitivity of the used landscape metrics as a result of the more or less complete representation of the ecological landscape structure (Bastian et al., 2006; Klein et al., 2009; Lausch and Herzog, 2002). These kinds of statistical zones seem to be less affected by the effects stated above.

2.2. Scale and statistical unit size

The presented ZonalMetrics toolbox enables the calculation of the given landscape metrics at any scale, grain, and extent, according to user-defined units and using a user-defined categorical vector layer (e.g. land use/land cover (LULC), habitat layers). It is widely agreed that the scale of the analysis can significantly influence the conclusions, and that landscape metrics are known to be sensitive to grain and scale (Baldwin et al., 2004; O'Neill et al., 1996; Szabó et al., 2014; Turner et al.; 1989; Wu et al., 2002; Wu, 2004). Therefore, the approach to the interpretation of the results of zonal landscape metrics calculation is to be discussed in the context of the components of scale. The grain is defined by the smallest feature of the analyzed categorical vector layer. The extent of the analysis is commonly understood as the size of the study area (Turner et al., 1989) and in the context of landscape metrics, it is usually applied as the landscape level of analysis (first defined by McGarigal and Marks, 1995).

The zonal level of landscape metrics calculation changes the understanding of the term *extent* to the individual statistical zone where the local variance is captured. These zones may be freely compared to each other according to users' needs. Therefore, the landscape is analyzed as a set of statistical zones. However, aggregation of their values to obtain the landscape level of analysis is not

Table 1
Tools for zonal metrics calculations available in the ZonalMetrics toolbox.

Group of metrics	Tool name	Calculation	Formula (McGarigal and Marks, 1995, modified)
AREA	**Class Area (CA)**	Area of the patches of the corresponding class within the statistical zone (calculated for each selected class)	$CA = \sum_{i=1}^{n} az_{ij}$
	Number of patches per class (NPC)	A number of patches for each corresponding class within the statistical zone.	$NPC = nz_i$
	Zone Area (ZA)	Area of the statistical zone in which landscape metrics are calculated (e.g. the area of single hexagon/single pie or any other zone).	$ZA = TAz$
	Percentage of zone (PZONE)	Percentage of the area of the corresponding class per statistical zone.	$PZONE = CA/ZA*100$
	Largest Patch Index (LPI)	Looks for the patch covering the largest area within the statistical zone, calculates the area of this patch (LPI) and identifies the class of that patch.	$LPI = \max(az_{ij})$
EDGE	**Total Class Edge (TCE)**	Calculates Class Edge length (TCE) for edges of all patches of the selected class (es) (aggregated) within the statistical zone	$TCE = \sum_{k=1}^{m} ez_{ik}$
	Edge Density (ED)	The length of the edges within the statistical zone per area defined by the user (1 000 ha is the default setting).	$ED = TCE/ZA*DA$
DIVER–SITY	**Diversity (SHDI)**	Shannon diversity index (SHDI) per zone, based on the selected classes.	$SHDI = -\sum_{i=1}^{m} Pz_i \ln Pz_i$
CONTRAST	**Contrast Class Edge (CCE)**	The edge length of a selected focus class sharing a boundary with corresponding contrast classes (calculated per class). Percentage of the edge length of the focus class shared with contrast classes (Fig. 3b).	$CCE = \frac{\sum_{l=1}^{m} ezs_{il}}{TCE}*100$
CONNECTANCE	**Connectance Index (CI)**	Explores connectedness within the statistical zone within a defined distance:	
		Connectance Index - the number of distinct connected patches (may be used to assess a number of functional joins between these patches (McGarigal and Marks, 1995)).	$CI = nzc_i$
		`Area of parts of patches within the range of connection and its percentage per statistical zone area.	$PCIA = \frac{\sum_{j=1}^{n} acz_{ij}}{ZA}*100$
		Area of connection zone between two patches and its percentage per statistical zone area.	$PCIZA = \frac{\sum_{k=1}^{m} aczz_{k}}{ZA}*100$
		An optional connection layer is generated to show the areas of connection between the patches within a defined distance.	

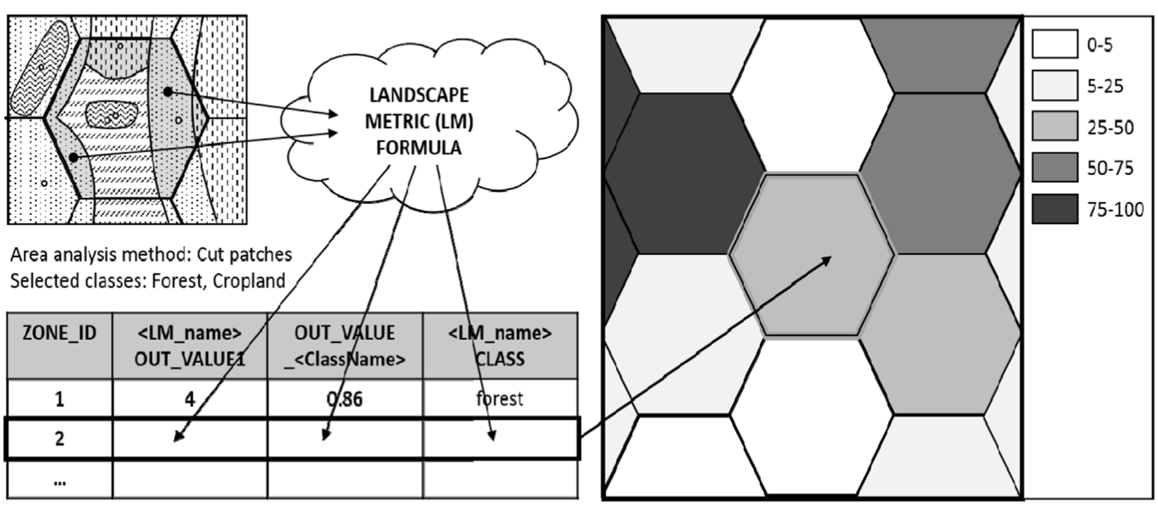

Fig. 2. Overview of the ZonalMetrics toolbox workflow: patches of the corresponding class are analyzed per zone, and the results are aggregated to the individual zones.

recommended (Hunsaker et al., 1994; Turner et al., 1989). For example authors (Baldwin et al., 2004; Turner et al., 1989) indicate that some metrics (e.g. Dominance, Contagion, Shannon's and Simpson's diversity indices, Mean Patch Size) are sensitive to the area of calculation with nonlinear relationships. The determination of the statistical zone extent (individual unit) remains a challenge, especially when regular tessellations are used. The literature provides no consistent recommendation regarding grid optimization in relation to the grain of a processed categorical layer and the characteristics of the analyzed phenomenon. Nevertheless, some estimates are available (compare Barreto et al., 2010; Hassett et al., 2012; Heinonen, 2007; O'Neill et al., 1996; Schindler et al., 2008).

The extent is fixed when landscape units, watersheds, or administrative units are applied. Still, the level of organization captured by the zone should not be disregarded because a landscape metrics calculation on units that are too homogenous causes a loss of expressiveness.

2.3. Assumptions for selecting a set of landscape metrics

Not all landscape metrics are best calculated on a zonal level. This is due to the specific conditions for calculating landscape metrics within statistical zones, which are considered as small subsets of the land-

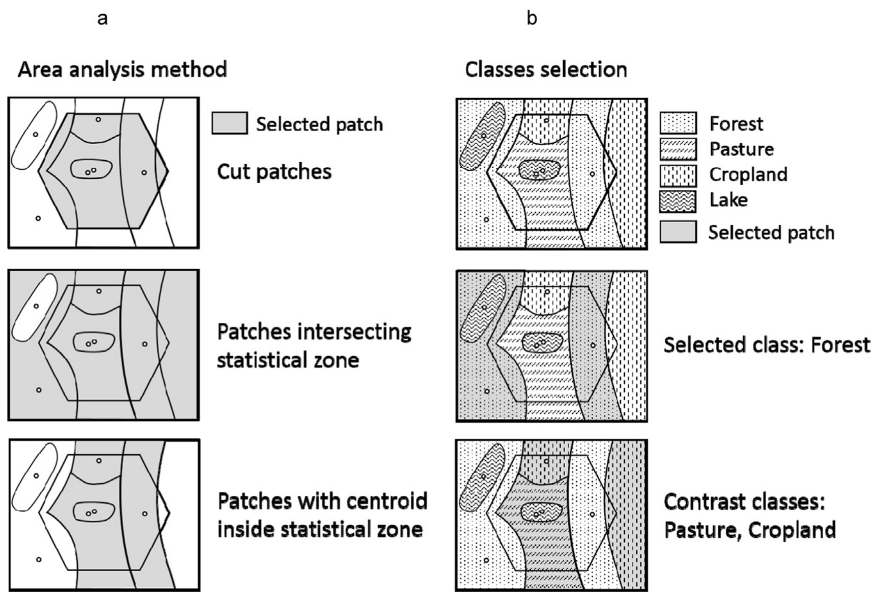

Fig. 3. Presentation of the different calculation options for patch selection and class selection within the ZonalMetrics toolbox: a) examples for patch selection methods for zone analysis; b) examples for class selection - an option available in all tools, and its use for contrast classes selection as implemented in the Contrast Class Edge (CCE).

scape. To meet these conditions, the following assumptions are made for implementing a specific set of landscape metrics facilitating the calculation and the interpretation of the results within zones:

- The simpler the equation of the landscape metric the lower the bias of the calculated estimator (Hassett et al., 2012). The additional advantage is the easier interpretation of the results.
- Area weighted metrics should be implemented to avoid the bias in the results when irregular statistical zones are used. This also applies when the calculation is done with the option of cutting the tessellations with the border of the study area.
- The limited extent of the analysis causes metrics that investigate the configuration of all patches across the whole landscape to be of limited use, and its results should be interpreted in a different way (e.g. diversity, equality of distribution, dominance, cf. Hunsaker et al., 1994).
- Some of the landscape metrics are more sensitive to the insufficient number of classes present (Hassett et al., 2012; Hunsaker et al., 1994), and they should not be used for calculations within zones, for example, Simpson Diversity Index (SIDI) and Contagion (CONT).
- The metrics should be calculated excluding artificial borders introduced by cutting the test area to the statistical zones. This allows avoiding the effects on the results of metrics calculated with artificial edges reported by Hassett et al. (2012) and O'Neill et al. (1996).
- The patch truncation effect (Hassett et al., 2012), which appears when statistical zones cut the categorical layer, can be avoided for some applications by using modified settings of the method for area analysis. Two options are implemented that allow including patches overlapping the statistical zone without cutting them. However, the results of such methods of calculation should be interpreted with caution and only in relation to the individual statistical zone.

3. Developed tools

The ZonalMetrics toolbox is an application written and implemented as a Python toolbox in ArcGIS, the source code is free and open to the community. Such Python toolboxes were introduced with ArcGIS version 10.1 and have the advantage over conventional tools in ArcGIS that their code and user interface to access the tool in ArcGIS are combined in one Python script. The script defines the available tools and their user interfaces (parameter selection, I/O data) as Python classes and includes the code for the execution of the tools. The tool itself makes use of the ArcPy site-package offering access to the complete geoprocessing functionality of ArcGIS as well as direct access to process and manipulate the geometry on a single feature basis (ArcGIS is required to run the tool). By using new cursors classes within the ArcPy data access module the performance of the tool could be increased, since such zonal analyses require many spatial queries and intersect operations to be performed in the background.

The ZonalMetrics toolbox has two main components (see Fig. 1): (1) Zonal layer calculation and (2) metrics to be calculated within the zones based on layers representing e.g. landscape structure, LULC classifications.

The zonal layer calculation component enables the generation of tessellation layers used for the zonal calculations of the landscape metrics. In principle, the tool is designed to accept every polygonal shapefile or ESRI feature class as a zonal input layer. Both regular tessellations (such as square grids) and irregular (e.g. administrative units, landscape units) categorical layers can be used within the ZonalMetrics toolbox. While specific units can be provided by the user or can easily be created with standard GIS tools (e.g. creation of a layer of rectangular cells), the toolbox offers the additional functionality for the creation of layers containing two kinds of regular units that are usually not easily accessible using standard GIS tools:

- Hexagons – can be more appropriate units for statistical summaries than e.g. squared grids (see discussion in the introduction). The size of the hexagons is based on the user-defined height (shorter diagonal). The output hexagon layer can optionally be centered to the specific point (defined by the centroid of the given layer) to represent the relationship between the distance from this point and the values summarized within the hexagons.
- Pies – structures similar to pie charts, but with an equal arc length of each section, depending on the number of sections set in the tool options. The sections are geographically oriented, which means that the first sector is directed to the north and, e.g. when four sections are defined, the whole area will be divided into 90-degree sections directed to the four points of the compass. Application examples could be the analysis of urban sprawl or something similar where developments/landscape structures follow a radial direction (see case studies section).

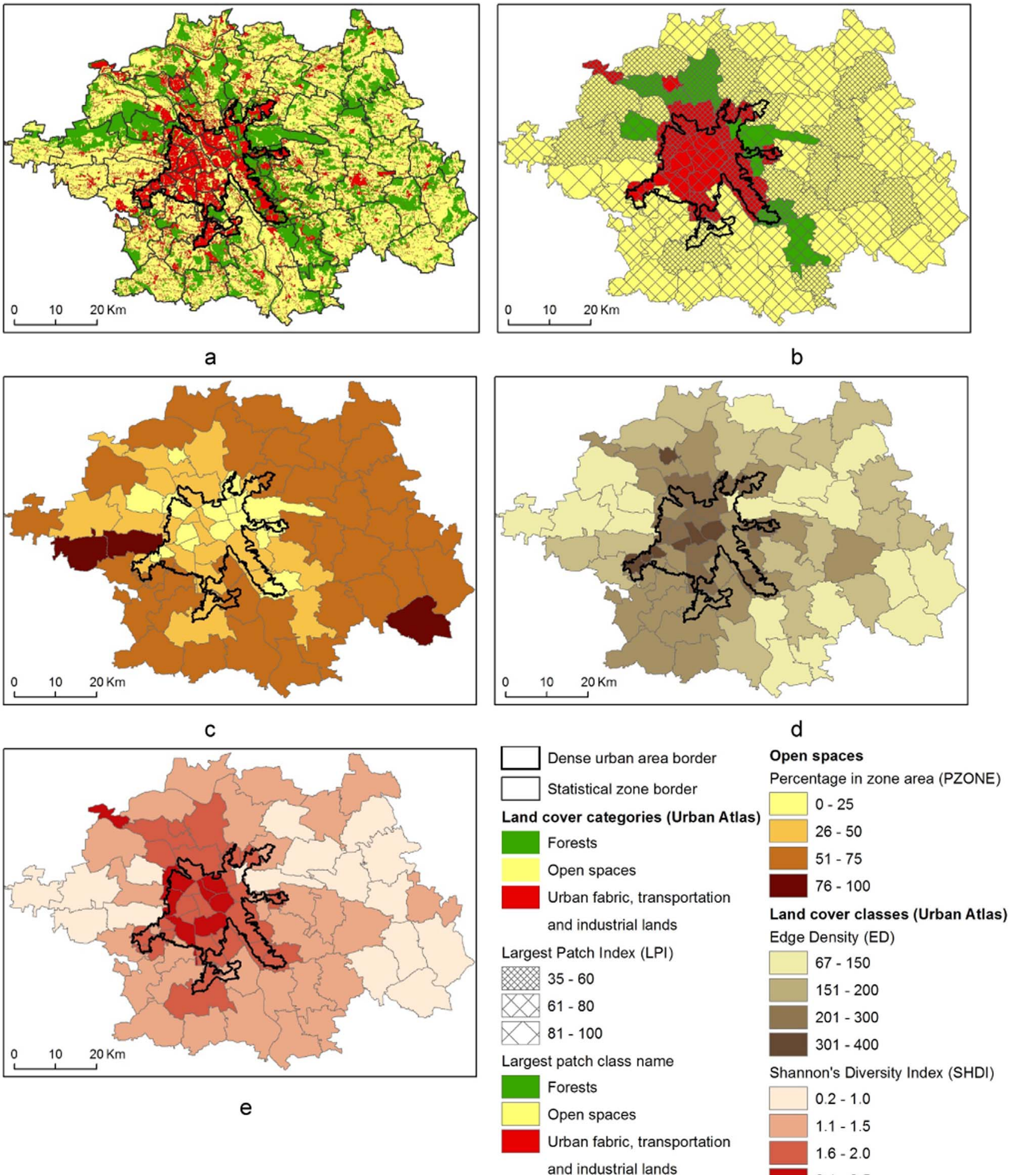

Fig. 4. Spatial distribution of the landscape metrics results calculated for administrative units based on the Urban Atlas data (EC, 2011) for the Warsaw metropolitan area (a): Largest Patch Index (LPI) and Largest Patch class name (b) of land cover categories; percentage of open spaces (c) within zone area (PZONE); Edge Density (ED) (d) and Shannon's Diversity Index (SHDI) (e) of land cover classes.

The metrics component contains a set of tools for landscape metrics calculation on the chosen zonal layer. An overview of these tools is presented in Table 1 with a description of the calculation method. The implemented metrics were selected based on their suitability to be calculated within statistical zones (see chapter above), representing each of the landscape metrics groups.

The workflow of the calculation of the landscape metrics within the ZonalMetrics toolbox is presented in Fig. 2. Two layers are required as input for each tool: (1) The input layer with categorical values e.g. LULC classes, for which the landscape metrics are calculated. The user can calculate the metrics for selected classes only. (2) The zonal layer in which the metrics will be calculated.

The toolbox offers three approaches for considering the patches in relation to the borders of the overlapping statistical zone (Fig. 3a):

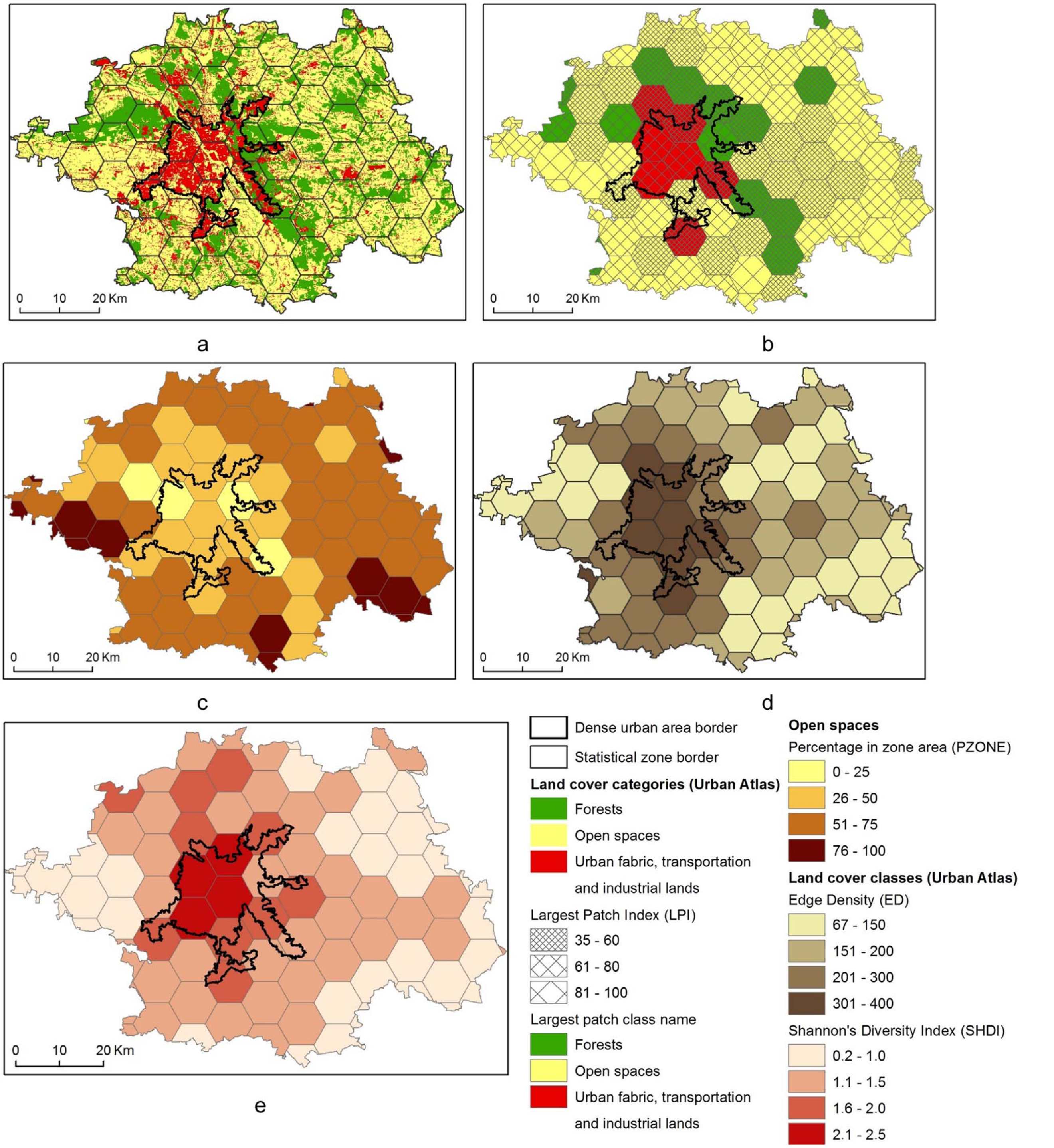

Fig. 5. Spatial distribution of the landscape metrics results calculated for hexagonal statistical zones based on the Urban Atlas data (EC, 2011) for the Warsaw metropolitan area (a): Largest Patch Index (LPI) and Largest Patch class name (b) of land cover categories; percentage of open spaces (c) within zone area (PZONE); Edge Density (ED) (d) and Shannon's Diversity Index (SHDI) (e) of land cover classes.

- Cut patches – the default method of calculation, where all the patches overlapping the statistical zone are clipped to the extent of the zone.
- Select overlapping – statistics are calculated for the whole patch if intersecting a given statistical zone, the same patch can be taken into account in several zones (double counting of intersecting patches).
- Select by centroids – statistics are calculated for the whole patch intersecting a zone if its centroid is located within the zone (no double counting of intersecting patches).

Where:
az_{ij} – Area of patch i within the statistical zone.
nz_i – Number of patches of the corresponding patch type(s) within the statistical zone.
TAz – Total area of the statistical zone.
ez_{ik} – Total edge length (in map units) of corresponding patch type within the statistical zone (zone boundary is not included in calculation).
DA– Density Area, defined by the user.
Pz_i – Proportion of the statistical zone area occupied by patch type i.

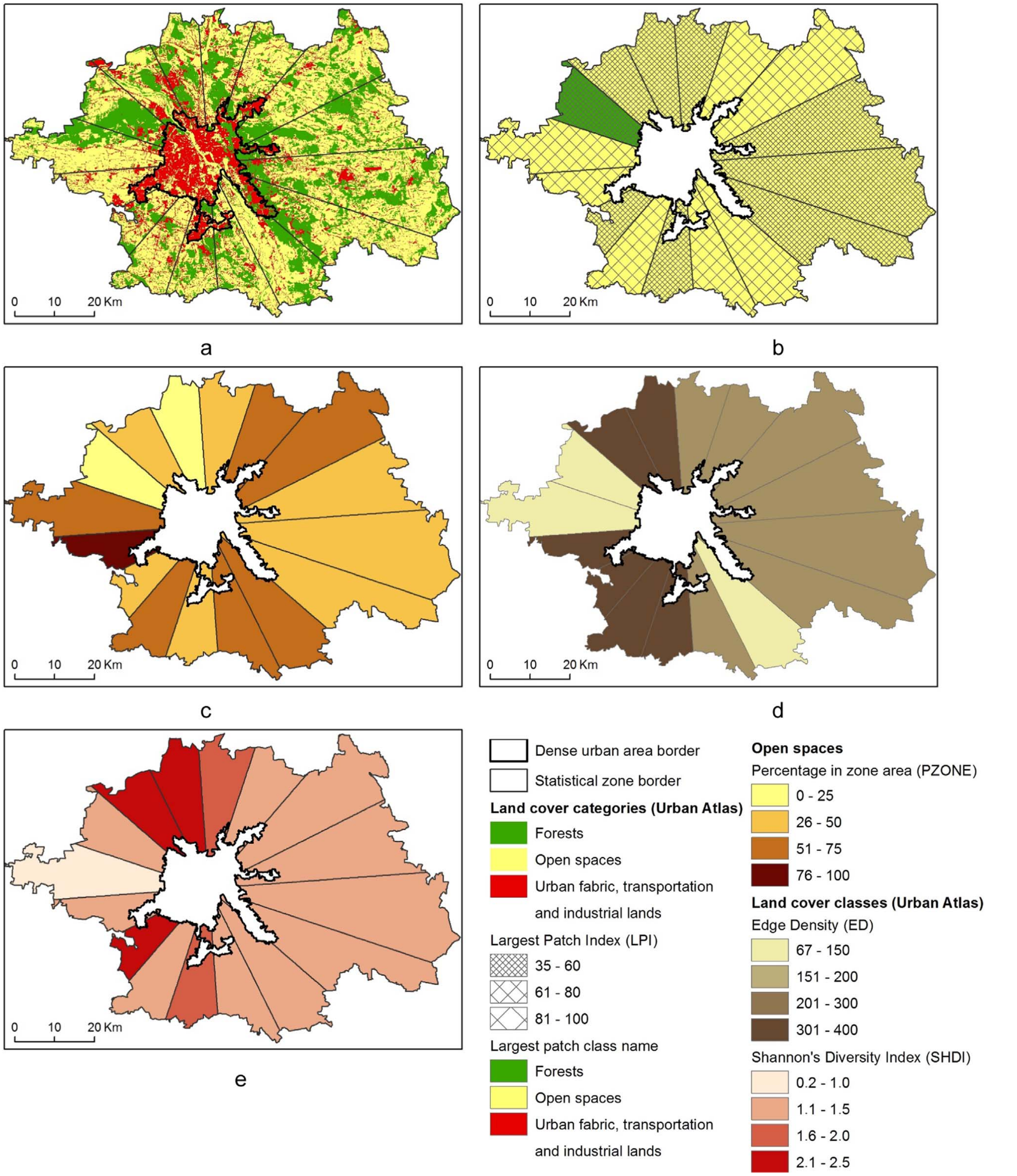

Fig. 6. Spatial distribution of the landscape metrics results calculated for pie statistical zones based on the Urban Atlas data (EC, 2011) for the Warsaw metropolitan area (a): Largest Patch Index (LPI) and Largest Patch class name (b) of land cover categories; percentage of open spaces (c) within zone area (PZONE); Edge Density (ED) (d) and Shannon's Diversity Index (SHDI) (e) of land cover classes.

ezs_{il} – Edge length (in map units) of selected class (i) sharing a boundary with corresponding contrast classes.
nzc_i – Number of connected patches of the corresponding patch type(s) within the statistical zone.
acz_{ij} – Area of patch ij within the statistical zone within the range of connection.
$aczz_k$ – Area of connection zone between two patches within the statistical zone.

4. Case study

The implemented metrics within the ZonalMetrics toolbox are exemplarily presented for a case study of the Warsaw Metropolitan Area (WMA), Poland. The main characteristics of the land cover in this area are related to the history of the urban development in the 1950–80 s. A high percentage of the open spaces (understood as agricultural areas and related classes) and forests is still present across the entire metropolitan area and within the administrative borders of Warsaw. Urban sprawl has influenced the land cover structure of this area since the political transformation in Poland in 1989. This results in highly spread small urban areas across the WMA. The freely available Urban Atlas (EC, 2011) was used as the LULC data set.

Different landscape metrics were calculated for three different kinds of statistical zones (see Figs. 4–6); abbreviations of the metrics are described in Table 1. The NUTS5 level was used as the administrative unit and the base management unit for this area. The regular tessellation layer was constructed of hexagons. The hexagon size was chosen according to the mean size of the administrative units (~8000 ha). Fig. 6 shows pie zones that were created to provide an example of how such non-standard statistical units can be used for the calculation of landscape metrics for directional studies. The metropolitan area was divided into the 18 sectors related to the cardinal and ordinal directions.

The landscape metrics for the statistical zones were calculated for two aggregation levels of the LULC data. Three aggregated categories of land use (forests, open spaces, urban fabric with transportation and industrial lands) (Figs. 4–6a) were summarized using the Largest Patch Index (Figs. 4–6b) to show which of them dominates within the zone and by how much. The percentage of the open spaces cover PZONE (Figs. 4–6c) was also calculated to show the proportion of the zone area which is not yet build-up.

The next two metrics were calculated for all Urban Atlas LULC classes. Both of them might be interpreted as a kind of representation of the complexity of the land use. In this context, Edge Density (Figs. 4–6d) is the highest in the dense urban area and if man-made structures occur in other classes (e.g. discontinuous urban fabric mixed with arable lands and semi-natural areas). Aside from the city borders, such values are related to the areas where intensive urban sprawl occurs. Shannon's Diversity Index (Figs. 4–6e) shows the diversity of land cover types within each zone, which is related to the abundance of functions fulfilled by these areas.

There is a difference between the interpretation and applications of these landscape metrics for each kind of statistical zone presented. Administrative units are frequently used for planning and management purposes. The results of landscape metrics may be used to identify the intensity of the urban sprawl and as one of the important factors to be taken into account in the development of the local management plans for each commune. Hexagonal statistical zones permit the evaluation of comparable units, which serve as a convenient basis for regional analysis and show easy to grasp spatial patterns for the whole area. With regular tessellation, it might be clearly shown where the urban sprawl is most intensive or which parts of this area are not yet affected. The same results shown with pies as statistical zones might not be significant in the above-given applications, aside from monitoring e.g. urban sprawl along the main communication routes. A high percentage of open spaces is conductive for fresh air supply, especially when it is related to the predominant wind directions (in the case of WMA these are west and south). In this context, the urbanization process with these areas might be interpreted as one of the main factors affecting local climatic conditions within the city.

5. Conclusion

The presented ZonalMetrics toolbox addresses the need for a practical and easy to use solution for the calculation of landscape metrics within zones. It widens the range of applications of landscape metrics, which can now be calculated for particular areas (any user-defined zones) within a study area. The results may be used in landscape evaluation for user-defined purposes. Zones of interest with a specific landscape structure can be identified (e.g. suitable for development, showing signs of disturbance). Landscape metrics calculated within zones may also support a more detailed regionalized landscape typology. The calculation in defined zones can also help with the interpretation of landscape changes over time by making changes spatially explicitly visible compared to landscape level analyses that usually only quantify the changes.

The current version of the ZonalMetrics toolbox contains the first set of landscape metrics, which we found to be most frequently used in the literature and which are valid to be applied in zonal approaches. Python scripting used in the development of the tool allows researchers to implement further metrics according to their needs, but also to use the calculations in batch mode for automated analyses. The source code is open to the community and available as a supplement to this paper as well as on ArcGIS Online (www.arcgis.com), a future implementation in an open source GIS software is planned.

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