MISCELLANEA GEOGRAPHICA – REGIONAL STUDIES ON DEVELOPMENT
Vol. 17 • No. 4 • 2013 • pp. 28-33 • ISSN: 2084-6118 • DOI: 10.2478/v10288-012-0045-y

Application of landscape metrics in the evaluation of geodiversity

Abstract
The purpose of this study is to present opportunities for using landscape metrics to evaluate geodiversity on individual landscape levels. The research area is located to the west of the Płock Urban and Industrial Agglomeration in Poland. Within this area, hierarchically organized regional units were delimited (Richling, Malinowska, Szumacher 2013). The area is divided into 87 first-level regions, 36 second-level regions and 9 third-level regions. The units have been treated as basic fields for geodiversity analysis purposes using selected landscape measures and metrics, to include area, density, size, edges and diversity (among others, Shannon's Diversity Index (SDI), Shannon's Evenness Index (SEI), domination (D) and redundancy (R)) generated in Patch Analyst v. 5, Fragstats v. 4.0, ArcGIS v.10 and Statistica v. 10 software.

Keywords
Geodiversity • landscape metrics

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Received: 3 October 2013
Accepted: 2 December 2013

Introduction

Landscape metrics (indicators) have become increasingly popular in determining landscape characteristics, both structural and functional. The structure is defined by metrics related to landscape configuration (situation of patches in space, isolation, contrasts) and composition (share and number of surface types, evenness indicators). They are most frequently used to evaluate biodiversity, geodiversity (Table 1), habitats, landscape heterogeneity and aesthetics, the effects of management and planning (e.g. the effects of landscape composition and configuration on water quality), as well as landscape functioning (the assessment of landscape mosaic and its changes, landscape monitoring) (Uuemaa et al. 2009; McGarigal, Tagil, Cushman 2009; Solon 2002).

Metrics-based landscape analysis is performed on a detailed level, with regard to its individual elements (patches) and selected components, but most of all in relation to the landscape as a whole. It consists of: (a) description of composition excluding spatial location (e.g. the number of landscape types, their share in space, evenness of distribution) and (b) a description of the configuration, i.e. spatial organization and relationship between landscape components (e.g. isolation, contrasts) (Richling, Solon 2011; Pietrzak 2010; Richling, Lechnio 2005).

For the purpose of formalized and methodologically unified procedures, software tools have been developed to allow fast and easy access to the required ratios. The tools include Fragstats (McGargial, Marks 1995) and Patch Analyst (Elkie, Rempel, Carr 1999). They allow both the use of commonly available raster data and topical studies in the vector format.

The practical use of landscape metrics to evaluate bio- and geodiversity focuses on such aspects as the optimum number of metrics, their appropriate informational connotation, including explicit assessment of analysed structural characteristics, and functional aspects in accordance with the landscape systematics applied (heterogeneity and taxonomy).

A number of authors (Cushman, McGarigal; Neel 2008; Uuemaa et al. 2011; DiBari 2007; Herzog, Lausch 2001) indicate that the purpose of the study and the nature of data used for analysis are decisive for metrics selection. Land cover maps are most frequently used (CORINE Land Cover), including data derived from processed satellite photos (single- or multispectral). Furthermore, the quoted authors point out the role of the scale of the study, to which the level of detail of the input data should be adjusted (Mander et al. 2005).

The input data format is another factor that affects the ambiguity of results. As previously stated, metrics can be calculated for a raster or vector image. Vector data are most frequently a product of the digitalization of topical maps or aero/satellite photos (segmentation, classification). In vector maps, patches have "hard" borders, and for methodological reasons, small patches are eliminated. In raster maps (aero/satellite photos or vector maps in the raster form) the borders are "soft" depending on the pixel size (resolution) and the applied classification of pixel-based patches (Alhamad et al. 2011). This may complicate delimitation of landscape classes due to the transitional (zonal) character of borders, which affects the calculated landscape metric values (in particular those regarding

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Table 1. Exemplary metrics (original nomenclature by McGargial, Marks 1995)

Landscape metrics	Authors
Geodiversity	
Patch Richness Density (PRD), Shannon's Diversity Index (SHDI), Shannon's Evenness Index (SHEI), Simpson's Diversity Index (SIDI), Simpson's Evenness Index (SIEI)	Benito-Calvo et al. 2009
Number of Patches (NP), Mean Proximity Index (PROX MN), Largest Patch Index (LPI), Patch Cohesion Index (COHESION), Total Core Area (TCA), Proximity Index Coefficient of Variation (PROX CV)	Alhamad et al. 2011
Shannon Index SHDI, Simpson Index SIDI	Nagendra 2002
Edge Density (ED), Simpson's patch diversity (SIDI), Simpson's patch evenness (SIEI), Largest Patch Index (LPI), Patch size coefficient of variation (AREA_CV), Mean Edge Contrast Index (ECON_MN), Total Edge Contrast Index (TECI), Shape Index Coefficient of Variation (SHAPE_CV), Fractal Dimension Coefficient of Variation (FRAC_CV), Euclidian Nearest Neighbour (ENN_AM)	Cushman et al. 2008
Edge Density (ED), Patch Density (PD), Mean Patch Area Distribution (AREA_MN), Mean Shape Index (SHAPE_MN), Contrast Weighted Edge Density (CWED), Percentage of Like Adjacencies (PLADJ), Contagion (CONTAG), Shannon's Diversity Index (SHDI)	Uuemaa et al. 2008
Mean Patch Size (MPS), The Landscape Shape Index (LSI) Simpson's Diversity Index (SIDI), the Interspersion and Juxtaposition Index (IJI)	Herzog, Lausch 2001
$G = \frac{NxR}{InS}$ G=Geodiversity, N=Number of physical elements in the unit, R=Rugosity, and S=Real surface, Ln=neperian logarithm	Serrano, Ruiz-Flaño 2007; Pellitero et al. 2011
Biodiversity	
Abundance, Absolute Richness, Shannon Diversity, Rarefied Richness, Functional Diversity, Size Diversity, Average tax. distinctness	Gallardo et al. 2011
Shannon Diversity Index (SHDI), Shape Index (SHAPE), Area Weighted Shape Index (AWSI), Nearest Neighbour Distance (NND), Proximity Index (PI), Mean Proximity Index (MPi), Mean Neighbour Patch Value Index ($MNPV_i$)	Kim, Pauleit 2007
Patch Density (PD), Largest Patch Index (LPI), Edge Density (ED), Proximity Index Distribution (PROX), Euclidean Nearest Neighbour Distribution (ENN), Perimeter Area Ratio Distribution (PARA), Shape Index Distribution (SHAPE), Related Circumscribing Circle Distribution (CIRC), Patch Richness (PR), Simpson's Diversity Index (SIDI)	Bailey et al. 2007
SIDI, CIRCLE_AM and IJI, ECON_MN, FRAC_MN, SHAPE_AM and AREA_CV	Schindler, Poirazidis, Wrbka 2008
Number of Patches (NP), Area Weighted Mean Shape Index (AWMSI) the Maximum, Minimum, Mean and Standard Deviation of Patch Size (MaxPS, MinPS, MPS, PSSD, respectively). Isolation - Mean Proximity Index (MPI).	Rocchini et al. 2006
Shannon Diversity Index SHDI (for number of types above 100) Simpson's Diversity Index SIDI	Yue et al. 2005
Mean Edge Contrast (MECI), Edge Density (ED), Mean Patch Size (MPS), Patch Size Coefficient of Variation (PSCV), Mean Fractal Dimension (MPFD), Mean Nearest Neighbour Distance (MNN), Mean Shape Index (MSI), Contagion (CONTAG), Cohesion, Interspersion/Juxtaposition Index (IJI), Patch Richness Density (PRD), Shannon's Diversity Index (SHDI), Simpson's Diversity Index (SIDI); Percent of Landscape (PLAND)	Kumar et al. 2006
ED or SIDI, TECI or ECON_MN, SHAPE_MN, and PRD	Uuemma et al. 2011
PLAND, AWMSI, CWED and IJI	Constible et al. 2006
Simpson Index of Diversity (SIDI), Edge Density (ED)	Massada et al. 2009
Shannon's diversity index, Simpson's diversity index, Simpson's evenness index	Onaindia et al. 2004
PD, LPI, PR, ED, ENNCV, PROXMN, CIRCMN and SIDI.	Bailey et al. 2007

borders, size and number of units). Such problems are mitigated during the interpretation of vector maps (Herzog, Lausch 2001). The pixel size may also affect landscape metric results and interpretation. Depending on the applied resolution, values of landscape metrics may vary (Yue et al. 2005; Huang et al. 2006).

Correct interpretation is yet another problem related to the use of metrics in landscape analyses. In particular, this is true for issues regarding the evaluation of processes (operations), which is indirectly characterized by such metrics as the largest patch index, mean nearest neighbour distance and cohesion/juxtaposition IJI. Core area indicators may also prove useful (Kupfer 2012).

Importantly, landscape metrics should be extended by those describing landscape functioning exceeding just the analysis of changes over time. Examples of applying such ratios to evaluate the pace of landscape changes may be found in studies by Ares

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Table 2. Minimum, maximum and average measure values and their variability within each regional classification level

	Name	SDI	SEI	TE	ED	MPE	MPS	NumP	PSSD	CA	PR	PRD	RPR	D	%LAND	PF	R	PD
Third-level regions	min	0.8701	0.4180	183409.10	26.14	6972.37	174.81	16.00	281.54	7015.86	4.00	0.0002	28.57	0.19	9.34	0.0300	0.32	0.0023
	max	1.4219	0.6834	1425215.08	43.13	11463.07	438.49	181.00	1172.09	37356.98	7.00	0.0007	50.00	0.97	70.40	0.2500	0.58	0.0057
	avrg	1.1245	0.5490	682188.85	36.46	8932.92	259.29	80.00	499.18	18435.04	5.36	0.0004	38.31	0.55	34.52	0.1073	0.45	0.0042
	dev	0.1969	0.0872	425340.18	4.93	1373.78	77.94	51.09	276.82	11343.22	0.87	0.0002	6.19	0.24	21.38	0.0650	0.09	0.0010
	Vs	17.5100	15.8821	62.35	13.51	15.38	30.06	63.86	55.46	61.53	16.15	43.8406	16.15	43.79	61.93	60.5932	19.10	23.5307
Second-level regions	min	0.0904	0.1305	23853.83	25.26	4946.99	86.22	3.00	68.86	540.15	2.00	0.0004	33.33	0.02	1.45	0.0741	0.14	0.0023
	max	1.6397	0.8625	398556.39	57.38	12345.47	438.49	54.00	1172.09	9502.49	7.00	0.0056	100.00	1.52	100.00	1.0000	0.87	0.0116
	avrg	0.8850	0.5677	168718.79	39.75	8628.51	234.57	20.18	353.54	4433.19	4.47	0.0014	77.64	0.59	26.35	0.2919	0.43	0.0051
	dev	0.3118	0.1536	75656.99	8.25	1877.19	86.25	9.62	206.45	2106.17	1.00	0.0010	18.93	0.36	22.34	0.1583	0.15	0.0021
	Vs	35.2373	27.0548	44.84	20.75	21.76	36.77	47.66	58.40	47.51	22.34	68.0730	24.38	61.15	84.75	54.2353	35.53	41.9179
First-level regions	min	0.0834	0.0759	11550.42	21.79	4526.78	69.87	2.00	9.04	220.91	2.00	0.0005	9.52	0.00	5.81	0.1667	0.00	0.0017
	max	1.5959	0.9952	200609.42	86.20	15976.43	588.32	22.00	1334.44	6064.78	6.00	0.0091	100.00	1.31	100.00	1.0000	0.92	0.0143
	avrg	0.7652	0.6352	69674.87	42.48	8867.70	244.06	8.25	298.38	1850.61	3.42	0.0027	73.40	0.41	41.64	0.4979	0.36	0.0056
	dev	0.3405	0.2181	35972.78	13.33	2832.84	132.88	4.35	237.46	1145.46	1.10	0.0017	23.57	0.28	19.32	0.2114	0.22	0.0032
	Vs	44.4994	34.3408	51.63	31.37	31.95	54.45	52.72	79.58	61.90	32.34	64.9186	32.12	68.32	46.41	42.4656	59.78	56.2815

et al. 2001, Jones et al. 2001, Uuemaa et al. 2005, Mander et al. 2005, amongst others.

Most studies devoted to the use of metrics to evaluate landscape diversity classify the Shannon and Simpson diversity and evenness indicators as universal. They complement each other, with the first regarding the number of types within a landscape and the second allowing assessment of the evenness of their share (McGargial, Marks 1995). Indicators used to evaluate the bio- and geodiversity of the landscape include Patch Richness Density (PRD), Shannon's Diversity Index (SHDI), Shannon's Evenness Index (SHEI), Simpson's Diversity Index (SIDI) and Simpson's Evenness Index (SIEI) (Benito-Calvo et al. 2009; Nagendra 2002; Kot, Leśniak 2006) (Table 1).

Another proposal of the geodiversity index is based on a correlation of the Earth's geodiversity elements (surface forms, erosion and accumulation forms, morphostructure, water, soil etc.) with surface roughness, which influences such processes as matter flow, heat supply etc. The formula is as follows:

$$Gd = Eg\ R / LnS$$

where Eg stands for the number of various abiotic components in a unit, R stands for the unit roughness indicator, and S stands for unit size in square kilometres (Serrano, Ruiz-Flaño 2007).

The objective of the study is to present opportunities for using landscape metrics to evaluate geodiversity on each landscape classification level. For this purpose, the research area has been subdivided into hierarchically organized natural units (see: Richling, Malinowska, Szumacher 2013). Individual typological landscape units were used to delimit regions. As a result, first-level regions (87), second-level regions (36) and third-level regions (9) have been determined. The regions have been treated as basic fields to analyse geodiversity, with selected landscape measures and metrics referring to their size.

Methods

The study utilized a set of landscape measures and metrics, as well as statistical ratios generated in Patch Analyst v. 5, Fragstats v. 4.0, ArcGIS v.10 and Statistica v. 10 (Table 2) [1]:

1. Space:
- Area: ha (CA),
- Share of region size in the upper grade region: percent (% LAND).

2. Density and size:
- Number of patches (NP),
- Patch density: number of patches/ha (PD),
- Mean patch size: ha (MPS).

3. Edge measures:
- Total length of patch borders in a region: m (TE),
- Average length of patch borders in a region : m (MPE),
- Edge density: m/ha (ED).

4. Diversity measures:
- Shannon's Diversity Index (SDI),
- Shannon's Evenness Index(SEI),
- Domination (D),
- Redundancy (R),

[1] Names and symbols of the characteristics comply with those used in the software.

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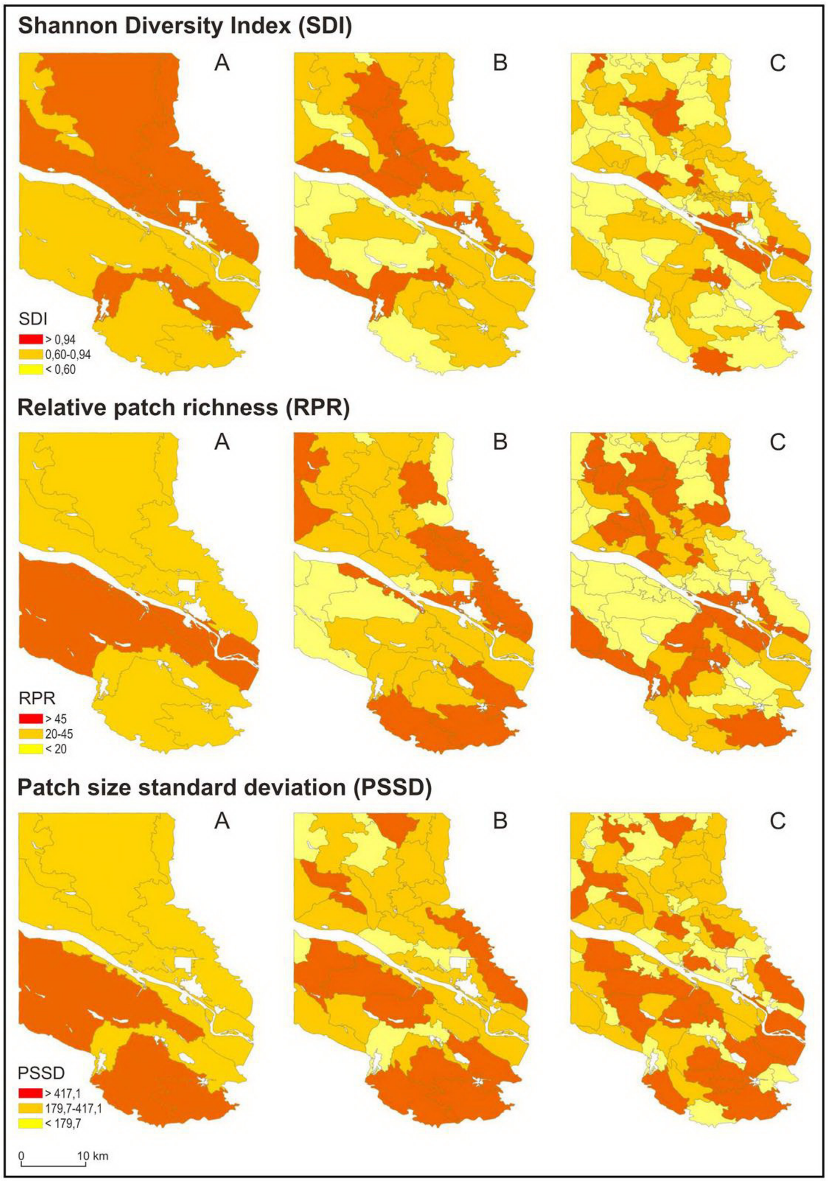

Figure 1. Distribution of selected landscape metrics. A – third-level regions; B – second-level regions; C – first-level regions

- Number of types in a region (PR),
- Patch richness density: number of types/sq. km (PRD),
- Relative density of types in a region (relative richness): % (RPR),
- Patch fragmentation per region: number of types/number of patches (PF),
- Standard deviation of patch size (PSSD).

A detailed description of methods applied and their diagnostic value in relation to landscape diversity is available in software documentation and extensive specialist studies (McGargial, Marks, 1994; Solon 2002; Kot, Leśniak 2006, Nagendra 2002; Urbański 2008; Eetvelde, Androp 2009). Indicators of space, density and size of patches and their borders are the key metrics determining landscape structure.

Results

Geodiversity within regions was determined through an evaluation of the diversity (richness) of types of individual patches defined based on abiotic landscape features and the evenness of their distribution within a given region.

The number of patch types (PR) within a region is not itself a sufficient parameter to assess its structural diversity. The diversified surface of regional units is the decisive factor (see: CA in Table 2), indirectly determining the probability of occurrence of a higher number of types. Among others, this is illustrated by the RPR ratio indicating the probability of the occurrence of all types in the region. The ratio is proportional to the spatial size (for the largest patches, this is close or equal to 100%). This relationship has not been proven: third-level regions with the largest size have the lowest maximum value (RPR – 50%). The RPR distribution within each region (Figure 1) illustrates the dependence of diversity on the scale of the study and patch size. For example, an area belonging to the third-level region 6 has a RPR above 45%, where lower-level analyses usually give the result below 20% (Figure 1).

Patch richness density (PRD) is another indicator of structural diversity. For the second and third-level regions, the value is

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similar, being significantly higher in first-level regions. Relatively small changes in the number of types, accompanied by the large disproportion in the size of the analysed patches, affect the final result, and therefore this ratio is not fully reliable either.

Shannon's Diversity Index (SDI) is also related to the surface of patch types. If a research area has a small mosaic structure, the index drops significantly, since it is sensitive to small-area classes (Solon 2002). For first-level regions, the maximum, minimum and average SDI values are the lowest, with the largest standard deviation (Table 2, Figure 1). Thus, the evaluation of geodiversity and functioning of a given area with metrics first of all requires the scale of the study (i.e. the level of regionalization) to be determined.

The most balanced proportions of type distribution within a region were achieved in first-level ones (11 regions). The average Shannon's Evenness Index there was 0.63, with a maximum as high as 0.99, meaning that the types occupy equal areas (Table 2).

A landscape metrics analysis for various level regions indicates certain dependencies between the landscape analysis level and recognition of its structure and geodiversity. Additional statistical analysis confirms the regularity. Mesoregion entropy is strongly correlated to the number of individual patches, their size and density. Additionally, surface forms affect the proportionality of patch type distribution. In third-level regions, landscape diversity is influenced mostly by lithology and soil. On the second-level region level, the correlation is much weaker, due to the higher variability of measures regarding area, density and area size in first-level regions. Entropy only indicates a correlation between the number of types, their density and form. The surface form is also correlated to the proportional distribution of types within a region. Similar trends are observed in first-level regions, where diversity is additionally affected by underground water.

Analysis of the distribution of key area, density, size and edge measures allowed the regularity of the hierarchical structure of regions to be determined. Region area (CA), number of individual patches included therein (NP), types (PR) and total edge length (TE) grow in proportion to regional grade. The highest variability is observed in first-level regions. Please note, however, that this is not sufficient to evaluate the diversity of a given region. The correlation does not exist for other measures, especially those including the region area (Table 2), i.e. PD, ED, PRD, RPR, MPS and MPE. Nevertheless, the measures vary the most in the smallest regional patches.

Conclusion

Geodiversity evaluated within the typological units for all metrics referred to herein does not indicate any fixed, directional relations to the regional classification level. Absolute measures of area, density, size and edges (CA, NumP, TE) increase with the regional classification level. This is the result of the higher heterogeneity of higher level units. Relative area measures (%LAND, PD, MPS, MPE, ED), including space, number or border length of landscape patches, do not show any significant regular changes depending on the regional classification level. Certain entropy measures, in particular Shannon's diversity and evenness indexes (SDI, SEI), as well as PSSD and R, vary proportionally to the regional classification level, which also depends on the increasing heterogeneity. No such regularity is observed in other diversity indicators surveyed, however. The researched area contains patches where no significant changes in entropy measures occur (SDI) regardless of the regional classification level. These are mostly plains with Aeolian and alluvial sands, i.e. areas whose genesis, structure, functioning and anthropogenic use are strictly determined. Clay plains, where the spectrum of characteristics (and therefore the complexity of landscape structure and functioning) is much higher, see a rapid drop in diversity for lower regional classification levels.

Acknowledgement

The paper was prepared under the research project of the Ministry of Science and Higher Education – project number N N305 322135 "Hierarchical model of the natural system and its use for biodiversity assessment and forecasting."

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