THEMATIC RESOLUTION IN CONSERVATION MONITORING - ASSESSMENT OF THE IMPACT OF CLASSIFICATION DETAIL ON LANDSCAPE ANALYSIS USING THE EXAMPLE OF A BIOSPHERE RESERVE

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With 11 figures and 4 tables
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Summary: Monitoring landscape changes, especially conservation sites, is essential to sustain the environment and landscape diversity (Townsend et al. 2009). By now, it is evident that the thematic resolution of classified data sets affects the results of land use/land cover and landscapestructure analysis. However, uncertainty regarding the ambiguity of classification schemes and the impact of generalizations have not been sufficiently addressed until now (Lechner et al. 2012). This study applies digital vector data of biotope types and land use mapping to gain further systematic insights into these questions. The data sets are available area-wide for 2 years (1993 and 2006), using the example of the Rhoen biosphere reserve situated in central Germany. The objectives of the study are 1) to consider the effect of thematic resolution on the magnitude of land use and land cover changes, 2) to assess the impact of thematic resolution on the analysis of landscape patterns, and 3) to investigate which thematic resolution is most suitable to detect differences between the biosphere reserve zones regarding the temporal development of the landscape structure. To achieve the objectives, the initial data are reclassified into data sets, encompassing 9, 27, 59, and 204 classes. Results indicate a considerable effect on the magnitude of detectable landscape changes at low or very high thematic resolutions and a high sensitivity of landscape metrics. However, landscape metric values show not only quantitative (discrepancies of values) but also qualitative (divergences of direction of change) impacts.

Zusammenfassung: Das Monitoring von Landschaften und insbesondere von Schutzgebieten ist zur Erhaltung der Umwelt und Landschaftsvielfalt unerlässlich (Townsend et al. 2009). Es ist offensichtlich, dass dabei die thematische Auflösung der verwendeten klassifizierten Datensätze Einfluss auf Ergebnisse von Landnutzungs-/-bedeckungs- und Landschaftsstrukturanalysen hat. Dennoch werden Unsicherheiten hinsichtlich der mangelnden Eindeutigkeit von Klassifikationsschemata und der Einfluss von Generalisierungen nicht ausreichend behandelt (Lechner et al. 2012). Um diese Zusammenhänge systematisch zu untersuchen, werden in der vorgestellten Studie Biotoptypen- und Nutzungskartierungen verwendet, die als Vektordatensätze vorliegen. Die Datensätze stehen flächendeckend für zwei Zeitschritte (1993 und 2006) für das Biosphärenreservat Rhön zur Verfügung. Mit der Studie soll der Einfluss der thematischen Auflösung von klassifizierten Datensätzen 1) auf die Veränderung von Landnutzung und -bedeckung sowie 2) auf die Analyse der Landschaftsstruktur ermittelt werden. Darüber hinaus wird untersucht, 3) welche thematische Auflösung am besten zur Analyse von unterschiedlich verlaufenden Landschaftsstrukturveränderungen in den Zonen des Biosphärenreservats geeignet ist. Um die Forschungsfragen zu beantworten, werden die Ausgangsdaten in 9, 27, 59 und 204 Klassen differenziert. Die Ergebnisse zeigen, dass bei geringen und sehr hohen thematischen Auflösungen der Einfluss auf die Landschaftsstrukturindizes und die feststellbaren Veränderungen der Landschaft besonders hoch ist. Allerdings zeigen Landschaftsstrukturindizes nicht nur quantitative (Unterschiede in den Werten), sondern auch qualitative (unterschiedliche Richtung der Veränderung) Beeinflussungen.

Keywords: Thematic resolution, landscape metrics, landscape change, GIS, Rhoen, landscape conservation, monitoring

1 Introduction

In many cases, landscape changes are the result of land use intensification, land use abandonment, and soil sealing. These changes often are accompanied by a loss of landscape diversity and associated ecosystem functions (Antrop 2004; Feranec et al. 2010; Nagendra et al. 2013; Ohnesorge et al. 2013). Monitoring landscape changes, especially conservation sites, is essential to sustain the environment and landscape diversity (Townsend et al. 2009). In the face of the progressive availability of high-resolution data and free access to satellite images, as well as the wide application of detailed biotope and land use mapping in conservation monitoring, the aggregation of categories into meaningful master classes is inevitable but challenging (Gähler and Schiewe 2007; Pontius and Malizia

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2004; Townsend et al. 2009). Hence, in the process of landscape-change analysis, landscapes are always simplified to varying degrees (Bailey et al. 2007).

The generalization and simplification of complex data sets cause uncertainty in the analysis of real-world phenomena that is not routinely addressed (Lechner et al. 2012). Although the impact of classification detail on the analysis of land use/land cover change can be substantial (Pontius and Malizia 2004), so far, only a few studies have assessed the impact of thematic resolution on quantitative landscape analysis (Buyantuyev et al. 2010; Buyantuyev and Wu 2007; Huang et al. 2006). Some studies that have dealt explicitly with thematic resolution have focused on modeling approaches regarding species diversity and distribution (Liang et al. 2013; Duro et al. 2014). However, most of the studies have analyzed the interrelation between landscape patterns and spatial scales (e.g. Kelly et al. 2011; Lustig et al. 2015; Saura and Martinez-Milan 2001; Turner 1989; Wickahm and Riitters 1995; Wu et al. 2000; Wu et al. 2002; Wu 2004). Thus, studies and applied research in landscape ecology and geography have dealt with the impacts of changing scale and resolution on quantitative landscape analysis for several decades but neglected the thematic resolution to a large extent (Castilla et al. 2009; Buyantuyev and Wu 2007; Lechner et al. 2012).

Considering landscape diversity is not only about the diversity of land use but also the diversity of structures and forms (Haber 2008, 92). Therefore, in the context of developing monitoring approaches, landscape metrics offer great potential to address landscape structural aspects, in addition to land use/land cover changes (Herbst et al. 2007; Huang et al. 2006; Lausch and Menz 1999; Uuemaa et al. 2009; Walz 2015). These landscape metrics facilitate a descriptive analysis of structural landscape properties (Dramstad 2009; Herbst et al. 2007) and are predestined to be used for monitoring procedures in conservation and planning (Lang and Blaschke 2007; Matusch et al. 2012; Walz 2013). However, they also are influenced by thematic resolution (Šímová and Gdulová 2012).

Previous research has demonstrated the effects of thematic resolution on landscape pattern analysis. Results have shown that i) landscape metrics are significantly dependent on thematic resolution (Bailey et al. 2007; Liu et al. 2013), ii) calculations of landscape metrics are influenced quantitatively and qualitatively (Kallimanis and Koutsias 2013), iii) so far, no threshold beyond which the effect of thematic resolution on landscape pattern analysis becomes insignificant has been identified (Castilla et al. 2009), and iv) responses of landscape metrics to changing classification detail are not predictable for all metrics (Huang et al. 2006). Preceding studies of landscape structure analysis have applied classified raster images with thematic resolutions ranging from a minimum of 2 classes (Bailey et al. 2007; Buyantuyev and Wu 2007; Castilla et al. 2009; Herold and Menz 2001; Huang et al. 2006) to a maximum of 47 classes (Bailey et al. 2007). However, studies investigating the impact of classification schemes with 50 classes or more are lacking. Thus, investigating the strengths and weaknesses of landscape pattern analysis based on very high thematic resolutions (Kupfer 2012) and assessing the sensitivity of landscape metrics regarding changing thematic resolution remains a major challenge (Bailey et al. 2007).

Landscape change and landscape pattern analysis play important roles in monitoring biosphere reserves. Among the different types of conservation sites, biosphere reserves stand out in terms of their inclusive objectives to sustain the dynamics of landscape through integrating land uses in varying intensities (Ohnesorge et al. 2013). Therefore, it is important to monitor landscape changes in different management zones whose emphases range from total protection to land use development (UNESCO 2002). In many cases, biotope mapping, which comprises a huge amount of categories, is employed by local environmental authorities. Consequently, categories must be aggregated into meaningful land use/land cover classes or certain categories are excluded from analysis to manage the issue of change analysis (Gähler and Schiewe 2007). Uncertainties regarding the impact of category aggregation on the results and suitability of input data sets remain (Kinkeldey 2014; Lechner et al. 2013). Further investigations are needed to assess the effects of very high thematic resolutions (> 50 classes) on quantitative landscape analysis conducted with vector data sets in the context of monitoring tasks. There are several reasons for this: i) Many studies apply aerial photography, which enables a high thematic resolution, and results are usually retained as vector data (Lechner et al. 2012); ii) the amount of free satellite imagery has increased and, accordingly, classified satellite data are increasingly used in landscape analysis (DeVries et al. 2015; Lechner et al. 2012); iii) the increasing availability of high-spatial-resolution satellite images (e.g., QuickBird and

RapidEye) enables progressively higher thematic resolutions (e.g., Erasmi et al. 2013; Förster et al. 2008; Schuster et al. 2012); and iv) the application of vector data is prevailing not only with regard to biotope mapping based on photo interpretation techniques but also in the field of land cover maps created with newer object-based image analysis (Blaschke 2010; MacLean and Congalton 2013).

Thus, the objectives of this study are 1) to consider the effect of thematic resolution ranging from 9 to 204 classes on the detectable magnitude of vector-based land use and land cover changes, 2) to assess the impact of thematic resolution ranging from 9 to 204 classes on the vector-based calculations of landscape metrics, and 3) to investigate which thematic resolution is most suitable to detect differences between the management zones of a biosphere reserve regarding the temporal development of the landscape structure. Therefore, the study area is briefly introduced (Chapter 2) before data sets and methods are described in detail (Chapter 3). Then, the results are presented and discussed (Chapters 4 and 5), followed by a conclusion of the findings (Chapter 6).

2 Study area

The UNESCO biosphere reserve, Rhoen, is situated in the border triangle of 3 German federal states: Hesse, Thuringia, and Bavaria (Fig. 1a). Disregarding the expansion of the biosphere reserve in 2014, it stretches over 185,000 ha (Jedicke 2013). UNESCO officially deemed Rhoen a biosphere reserve in 1991. The main objectives of biosphere reserves are to sustain cultural landscapes by applying traditional land use and to combine the protection of biodiversity with sustainable economic systems (UNESCO 2002). Hence, landscape is recognized as a dynamic concept that is subject to ongoing changes and alterations (Erdmann 1997). To implement the different functions (i.e., conservation, development, and research), the area is organized into 3 interrelated zones: core area, buffer zone, and transition zone (Fig. 1b). Only the core area must be under legal protection to fulfill the function of nature conservation (UNESCO 2002). Geographically, Rhoen is a low mountain range, and its character is captured by the slogan “land of open vistas” (Jedicke 2013). Naturally, the area would be covered by beech forest, but extensive clearing and farming transformed

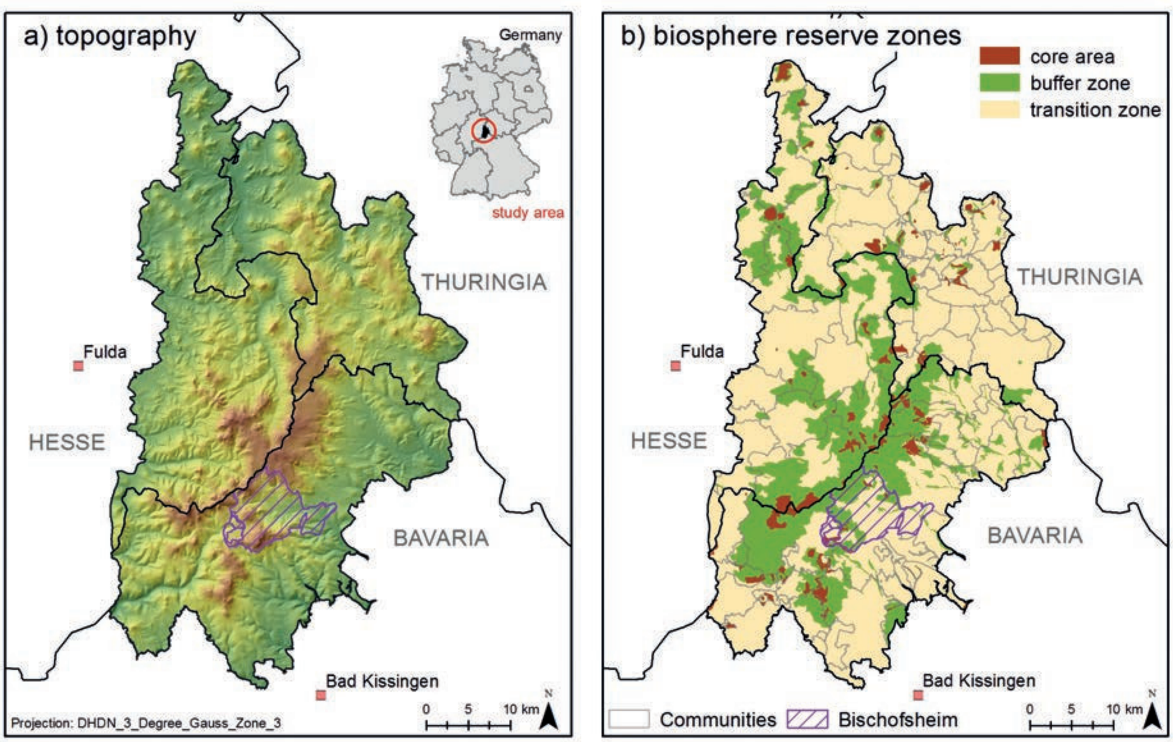

Fig. 1: Study area: a) location and topography of the biosphere reserve, Rhoen, in the border triangle of the German federal states of Hesse (HE), Thuringia (TH), and Bavaria (BY), community used for validation is highlighted; b) biosphere reserve zones and administrative boundaries (community level), community used for validation is highlighted. (Data sources: a) Bundesamt für Kartographie und Geodäsie, Frankfurt am Main 2011, b) Thüringer Landesanstalt für Umwelt, Jena, Thüringer Landesvermessungsamt)

the region into submontane grasslands with numerous woodless hilltops (e.g., Wasserkuppe up to 950 m; Behnen 2011; Mertz 2000). The rural, sparsely populated region is marked by pronounced landscape heterogeneity and distinct structural diversity as a result of age-long traditional land use (Grebe and Bauernschmitt 1995; Schenk 1993).

3 Data and methods

The analysis was conducted using digital data of biotope types and land use mapping that are available area-wide for the biosphere reserve for the years 1993 and 2006. Data are provided by the GIS section of the Thuringian biosphere reserve administration. It is a vector data model representing discrete boundaries of biotope types and accompanied land use types. An 11-digit code is used to describe more than 900 different main types, which are further differentiated using additional attributes. The combination of the first 4 digits distinguishes the ecosystem types. There are 204 different ecosystem types in the study area. These are used as the highest thematic resolution (Level 4, Tab. 1). Based on this aggregation, the ecosystem types are further summarized into meaningful land use/land cover classes, representing Levels 3 to 1 of the thematic resolution (Tab. 1). Level 1 land use/land cover classes encompass cropland, meadows and pastures, forest, other vegetation, swamp/peat bog, open area (e.g., rocks and bricks), open water, built-up/traffic area, and other areas (e.g., waste disposal sites). For convenience and readability, both ecosystem types and land use/land cover classes are referred to as *classes* in the subsequent text.

To validate the data sets, a subset is selected in terms of a community (Bischhofsheim, Fig. 1), which is representative of relief, percentages of biosphere reserve zones, and percentages of main land-cover classes (grassland and forest). Based on the 2006 data set, 5 % of all patches (≙ 331 patches) are randomly selected and visually compared to digital aerial photographs that were acquired by the federal state government in 2005. Due to quickly changing land uses, like construction sites, 28 of 331 patches were excluded. More than 94 % of the remaining 303 land use/land cover patches are equal to the visible land use/land cover patches. For 89 % of all patches, the boundaries precisely matched as well with the visible land use/land cover patches. Based on the validation check, the data set appears to have a high accuracy, which also is described in the final report on biotope mapping (Weyer 2008).

Tab. 1: Level of thematic resolution according to the number of classes

Level 1	Level 2	Level 3	Level 4
9 classes	27 classes	59 classes	204 classes

The land use/land cover change analysis is applied on the vector data set in the ArcGIS version 10.3.1 software package. That is feasible because the polygon areas of the 2 data sets are aligned to each other. Applying vector data prevents information loss in the process of vector-to-raster conversion and precludes an alteration of the shape of land use/land cover shapes that are of interest in the landscape structure analysis (MacLean and Congalton 2013). Furthermore, this approach seems preferable to gather novel insights, especially against the background that conservation and planning administrations employ vector data to a large extent (Gähler and Schiewe 2007; Walz and Wagenknecht 2010), and vector-format maps are consistently more favored as classification techniques advance (MacLean and Congalton 2013). A cross-classified table was created to investigate changes and calculate the magnitude of the land use/land cover changes for each thematic resolution level. The first step to assess the impact of thematic resolution on change analysis is comparing the proportion of changed and unchanged areas. Results also are displayed in maps that show the areas that are affected by land use/land cover change for each thematic resolution separately. The second step is calculating the ratio of change. The ratio of change is a measure to express the proportion of changes of a higher resolution level that is detected by a lower resolution level (Köhler 2009; Townsend et al. 2009). Thereby, it is possible to express how much of the change detected on a higher thematic resolution also can be explained by using a lower thematic resolution.

The landscape structure analysis is realized using Patch Analyst 5 software. Patch Analyst is an extension of ArcGIS that facilitates the spatial analysis of landscape structure based on vector data (Rempel et al. 2012). The multitude of landscape metrics may cause redundant information, as metrics often are correlated with each other (Herbst et al. 2007; Riitters et al. 1995). Therefore, a set of significant metrics should be selected (e.g., Lang and Blaschke 2007; Lausch and Herzog 2002; Townsend et al. 2009). Based on the calculation of the Spearman correlation coefficient for different groups of metrics, 7 metrics were selected from the list of those available in Patch Analyst (Tab. 2, Köhler 2009). Table 2 shows associated questions that can be answered by applying the metrics in a monitoring process. The Shannon diversity index

Tab. 2: List of applied landscape metrics and associated monitoring questions

	Abbreviation	Landscape Metric [unit, value range]	Monitoring question
Landscape diversity	SDI	Shannon diversity index [nondimensional, 0-∞]	How does the diversity change over time?
	SEI	Shannon evenness index [nondimensional, 0-1]	Are the various land use/land cover classes at the conservation site becoming more evenly distributed?
Shape analysis	MSI	Mean shape index [nondimensional, 1-∞]	Do the land use/land cover classes become more irregularly shaped over time?
	AWPFD	Area weighted mean patch fractal dimension [nondimensional, 1-2]	Do land use/land cover patches become more complex or fractured over time?
Area analysis	MPS	Mean patch size [hectare, -]	How do patch sizes change over time?
	MedPS	Median patch size [hectare, -]	How do patch sizes change over time?
Edge analysis	ED	Edge density [meters/hectare, -]	How does the edge density of the conservation site change over time? Is the landscape increasingly fragmented or is there a loss of structural diversity?

Sources: Lang and Blaschke 2007, 223–228; Kelly et al. 2011; Rempel et al. 2012

(SDI) is a relative measure of landscape diversity. If there is only one patch type in the landscape, the index equals 0. The Shannon evenness index (SEI) measures the distribution and abundance of patch types in the landscape. Values approaching 1 indicate evenly distributed patch types, whereas if the distribution is low, the value is equal to 0. Values of the mean shape index (MSI) increase with increasing patch shape irregularity, and values equal 1 if patches are circular. The area weighted mean patch fractal dimension (AWPFD) is another measure of shape complexity that is independent of patch sizes. Values approaching 1 indicate shapes with simple perimeters, and higher values indicate that shapes are more complex. Comprehensive descriptions of the landscape metrics can be found, for example, in Lang and Blaschke (2007). In addition, the number of patches is calculated for each data set for further insight regarding the data structure.

Prior to the landscape metric calculation, a mixed model is applied for each year to examine the data and to check whether the selected indexes pass the significance test. The one-factorial mixed effects model uses the thematic resolution as fixed effects and incorporates a random effect, which is the study unit in this study.

Subsequently, selected landscape-level metrics are calculated for the whole study area and for each community differentiated by thematic resolution levels. The results are compared using suitable charts, and for the latter, results also are mapped in ArcGIS to allow a spatially explicit interpretation. Therefore, the global minimum and maximum are derived from each landscape metric's data sets, and the same classification scheme is applied to each thematic resolution and time step to ensure comparability. In the final step, the issue of differences between the biosphere reserve zones is addressed. In accordance with Buyantuyev and Wu (2007), questions of whether thematic resolution considerably impacts the ability of landscape metrics to detect temporal changes and whether there is an "optimal" thematic resolution for change analysis are asked. Therefore, landscape metrics are calculated for the 3 different zones based on the different thematic resolutions and differentiated by the 2 time steps.

4 Results

4.1 Impact on land use/land cover change

To address Objective 1, the impact of thematic resolution on land use/land cover change is analyzed for the entire study area. Increasing classification detail enables detectable changes (Fig. 2 and Fig. 3). Applying the lowest thematic resolution, which dis-

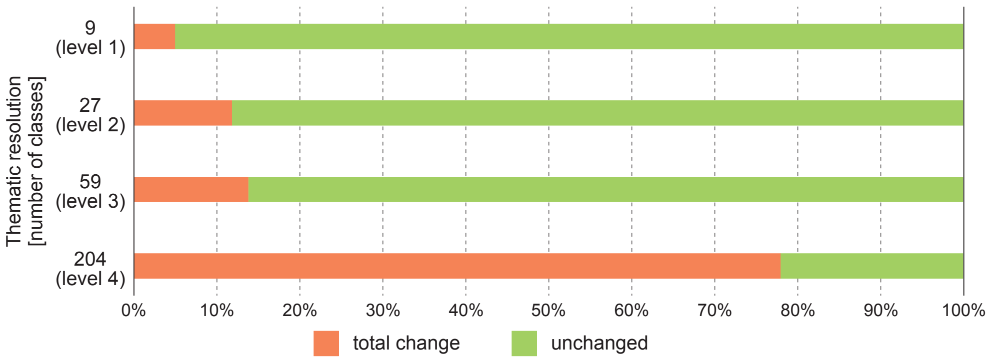

Fig. 2: Percentage of total change associated with different thematic resolutions

tinguishes only 9 classes, detectable changes in land use/land cover between 1993 and 2006 are close to 5 % of the total area. If Level 2 or Level 3 of the thematic resolution (27 and 59 classes) is applied, considerably more than 10 % of the area shows changes in land use/land cover. However, with a differentiation of 204 classes, land use/land cover changes are identified for almost 80 % of the total area (Fig. 2). The maps for Levels 1 to 3 (9 to 59 classes) show the highest proportion of changes within the Thuringian section compared to the Hessian and Bavarian regions, which indicate slightly fewer changes. The map of the highest thematic resolution (204 classes) shows that a huge proportion of the total area is affected by changes between 1993 and 2006, irrespective of the federal state boundaries (Fig. 3). The results suggest that the effects of changing thematic resolution from Level 2 to 3 are minor compared to differences between Level 1 to Level 2 and Level 3 to Level 4 (Fig. 2 and Fig. 3). This is also feasible respective to the different intervals: Level 2 differentiates 3 times as many classes as Level 1, whereas Level 3 does only about twice as many as Level 2, and Level 4 does almost 4 times as many as Level 3 (Tab. 1).

The ratio of change supports the statement that differences between Levels 2 and 3 are minor compared to the impacts of Level 1 and Level 4 (Fig. 4). The bar chart demonstrates that more than 40 % (≙ 0.43) of changes that are identified with the Level 2 resolution are also detected if Level 1 resolution is employed. Compared to Level 3 resolution, around 35 % (≙ 0.37) of changes also are detected with Level 1, whereas a considerable 85 % (≙ 0.85) are identified with Level 2. Regarding the highest thematic resolution (Level 4), only a small amount of changes is detected if lower thematic resolutions are applied (less than 20 %).

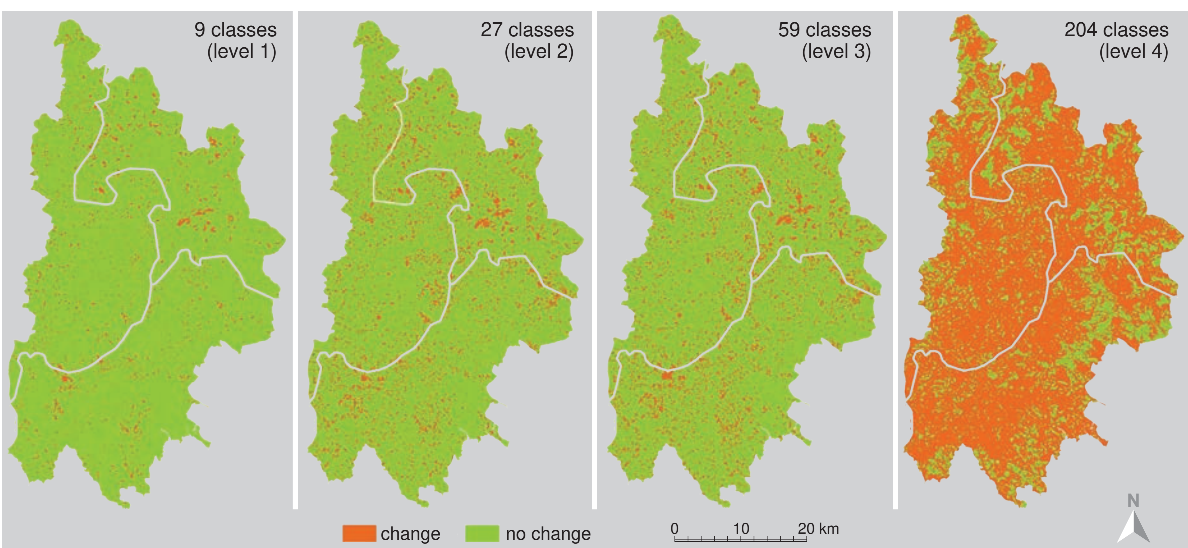

Fig. 3: Changed and unchanged areas of the biosphere reserve, Rhoen, between 1993 and 2006 for different thematic resolutions. (Data sources for administrative boundaries: Bundesamt für Kartographie und Geodäsie, Frankfurt am Main, 2011, Thüringer Landesanstalt für Umwelt, Jena, Thüringer Landevermessungsamt)

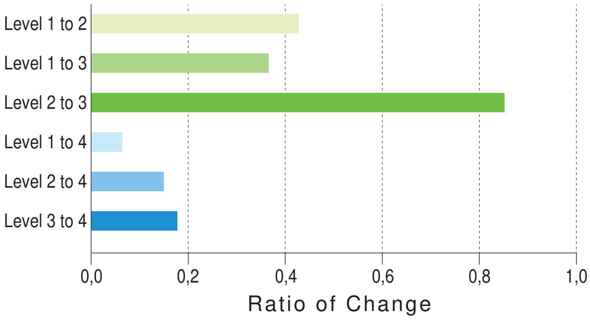

Fig. 4: Ratio of change for different levels of thematic resolutions (Level 1 ≙ 9 classes, Level 2 ≙ 27 classes, Level 3 ≙ 59 classes, Level 4 ≙ 204 classes)

4.2 Impact on landscape metrics

All of the selected landscape metrics passed the significance test of $p \leq 0.05$ (Tab. 3 and 4). Individual comparisons revealed that some of the metrics actually differed significantly for all thematic resolution levels (SDI, MPS, ED in 2006). The individual comparisons also can be plotted for the SDI, which is illustrated in figure 5. The figure shows that there is one significant overlap in 1993 regarding the Level 3 and Level 4 resolutions (59 classes and 204 classes) but no significant overlap for 2006.

Tab. 3: One-factorial mixed effects model for 1993, with study unit as random effect and thematic resolution as fixed effect (*significance criteria p ≤ .05). Note: Margins sharing a letter in the group label are not significantly different at the 5 % level

1993							
Index	SDI	SEI	MSI	AWPFD	MPS	MedPS	ED
p*	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Thematic Resolution							
9 classes				A			
27 classes		A	A	B	B	A	
59 classes	A	A	A	A B	A B	A	A
204 classes	A		A		A	A	A

Tab. 4: One-factorial mixed effects model for 2006, with study unit as random effect and thematic resolution as fixed effect (*significance criteria p ≤ 0.05). Note: Margins sharing a letter in the group label are not significantly different at the 5 % level

2006							
Index	SDI	SEI	MSI	AWPFD	MPS	MedPS	ED
p*	0.0000	0.0000	0.0000	0.0342	0.0000	0.0000	0.0000
Thematic Resolution							
9 classes				A B			
27 classes		A	A	B		A	
59 classes		A	A	A B		A	
204 classes			A	A			

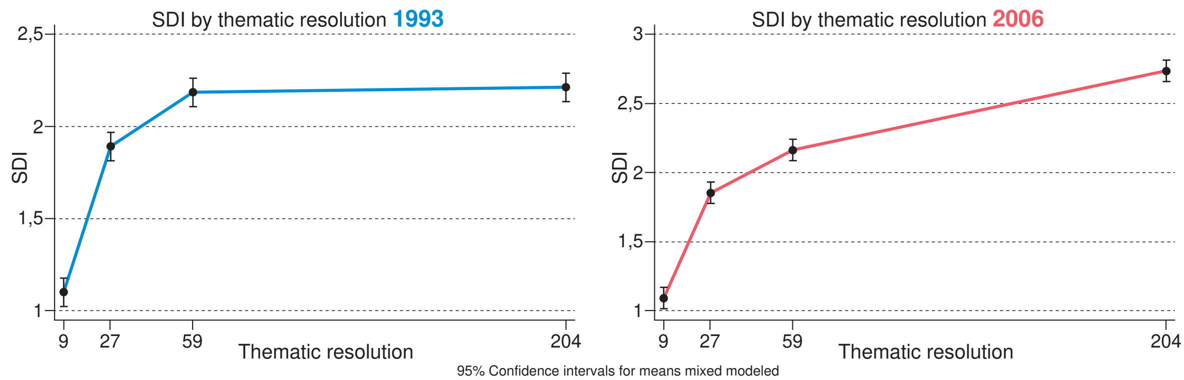

Fig. 5: Results of the one-factorial mixed effects model for the SDI. Means and 95 % confidence intervals are displayed for each thematic resolution. If confidence intervals overlap by more than half of another interval, the difference is not significant at $p < 0.05$

For many landscape indexes, the number of patches is an important parameter. It is obvious that with increasing thematic resolution, the number of patches increases as well. The line plot (Fig. 5) shows an abrupt rise in the quantity of patches between Level 1 resolution, distinguishing 9 classes, and Level 2 resolution, distinguishing 27 classes. The increased number of patches between Levels 2 and 4 still is considerable but flattened out. The higher number of patches for 2006 compared to 1993 might have been caused by higher-quality aerial photographs and sophisticated equipment to map biotope types and land use compared to 1993.

The results demonstrate that SDI, MPS, and ED values differ as a function of thematic resolution for both years (Fig. 6), whereas the SEI, MSI, AWPFD, and MedPS values show moderate changes due to classification detail. The values of SDI and ED increase with an increasing number of land use/land cover classes, while the values of MPS decrease. This is comprehensible, as the number of patches determines the amount of edges (ED) and the size of the patches (MPS). In addition, with higher classification detail, the identifiable diversity of the landscape (SDI) increases. The big gap between values of the first thematic resolution level and values of the following levels corresponds with the abrupt rise of the number of patches (Fig. 6). This also applies to the higher values of the highest thematic resolution for 2006 compared to 1993. However, the temporal changes could be caused by an actual increase of landscape diversity due to conservation strategies during the development of the biosphere reserve.

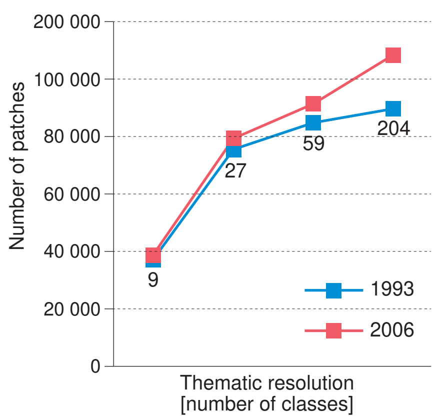

Fig. 6: Number of patches as a function of classification detail

The results of the landscape metrics calculated at the community level demonstrate more sophisticated but similar patterns compared to the results for the entire biosphere reserve (Fig. 7 and Fig. 8). Likewise, SDI and ED values increase and MPS values decrease with thematic resolution enhancement (Fig. 8). However, half of the SDI values are concentrated in a narrow range for the first 3 thematic resolution levels, exhibiting lower outliers. For the highest thematic resolution, there are few outliers, and the range of values excluding outliers is greater. The median of the SDI values in 1993 for the highest thematic resolution is closer to the medians of the next lower resolution than to the value of the same resolution in 2006. Only SDI and SEI values calculated with the highest classification detail (204 classes) suggest an increase of landscape diversity after the establishment of the biosphere reserve. Results indicate that the detection of temporal changes in landscape diversity is challenging if the thematic resolution is low. For example, results for SDI at Level 2 (27 classes) might even lead to the conclusion that landscape diversity slightly decreased between 1993 and 2006. The results of the ED calculations are less differentiated, and the increase of ED values is less distinct compared to the results of the total study area (Fig. 7), especially regarding the values in 2006 (Fig. 78 last boxplot). Moreover, MPS values seem to be less influ-

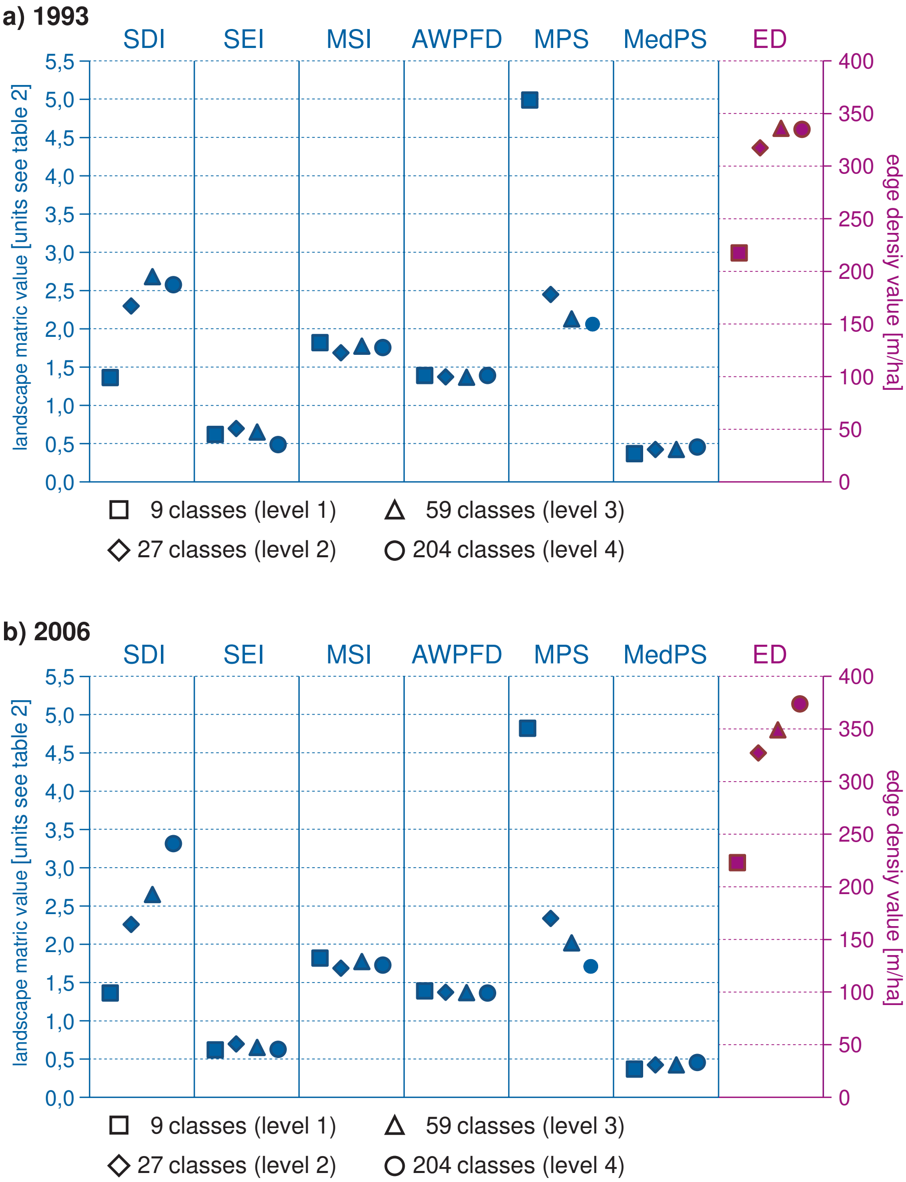

Fig. 7 Landscape metric values as a function of thematic resolution; above: values in 1993, below: values in 2006 (SDI: Shannon diversity index, SEI: Shannon evenness index, MSI: mean shape index, AWPFD: area weighted mean patch fractal dimension, MPS: mean patch size, MedPS: median patch size, ED: edge density)

enced by the thematic resolution if calculated at the community level than the results of the entire biosphere reserve indicate. Values of the lowest thematic resolution exceed the values of the other resolutions and exhibit a wider range. However, in contrast to the total study area, the values of Levels 2 to 4 exhibit only marginal variations when subjected to changing thematic resolutions. The results of the SEI calculation indicate a marginal impact of thematic resolution, though the slight decrease for the entire study area in 1993 is not confirmed in the boxplot (Fig. 7 and Fig. 8). It also is apparent that the number of extreme values and outliers decreases if thematic resolution increases. MSI and MedPS values show minor changes as a function of thematic resolution, which corresponds to the results of the total study area (Fig. 7 and Fig. 8). As the AWPFD is an area-weighted metric, the values of the entire biosphere reserve and the values of the communities were virtually equal and spanned only a narrow range (Fig. 8).

Results of landscape metric calculations at the community level are mapped in order to gain further insights into the interrelation between classification detail and landscape structure analysis and the spatial development of landscape patterns. The maps of SDI and SEI results are presented in this study to exemplify the findings (Fig. 9 and Fig. 10). The most-spatial variations for the SDI values become apparent with increasing thematic resolution (Fig. 9). Higher values are concentrated along the border of Bavaria and Hesse and in the southern parts of the biosphere reserve. This is coherent with the land use history and the actual landscape structure. Regarding monitoring objectives, Level 3 (59 classes) maps demonstrate an increase in landscape diversity in the southern parts, and Level 4 (204) maps show a pronounced increase of landscape diversity in several parts of the biosphere reserve. The spatial diversity of SEI values is even more pronounced (Fig. 10). It is striking that the spatial illustration of the lowest and the highest thematic resolution show a contrary picture of the SEI characteristic. For the lowest thematic resolution, forest-rich reference areas in the southwest and southeast of the study site are characterized by low SEI values. However, these areas show high values for the highest resolution. Areas in the north of the study site are marked by high values for the lowest resolution and low values for the highest resolution. Consequently, the impact of thematic resolution on landscape metrics is not only statistically evident, as shown in the boxplots, but also spatially relevant and even conflictive (Figs. 8, 9, and 10). As communities exhibit different surface areas, whether the extent impacts the landscape structure analysis was tested. For the areas under investigation, no significant correlation between the surface area of the communities and the metric values of landscape diversity and landscape evenness could be detected.

4.3 Impact on temporal changes of landscape metrics based on biosphere reserve zones

Thematic resolution has a significant effect on the ability of landscape metrics to assess temporal landscape patterns, which is revealed in figure 8 regarding the communities in the biosphere reserve. Another analysis was conducted to further investigate the impact on the temporal changes of landscape structure in the biosphere reserve's core, buffer, and transition zones. Except for the MPS and SDI values, results based on Levels 1 to 3 exhibited only minor temporal changes. A decrease of the SDI values in the core area is detectable only at Levels 2 and 3. The negative change in landscape diversity is inverted if the calculation is based on the highest thematic resolution (Level 4), which exhibits an increase of SDI in the core area. These conflicting results correspond to the findings based on the community level (Fig. 8). The increase of SDI values in the buffer and the transition zones seems to correlate to a decrease of MPS values. For the transition zone, a slight increase in SEI is evident. Comparing the results of Level 1 to Level 3, the patterns of temporal development of the landscape structure are related. An obvious difference can be identified only for the Level 4 (204 classes) results. The increase of landscape diversity, expressed by an increase in SDI and SEI and a decrease in MPS, confirms the previous results. The highest increase in the transition zone and the lowest increase in the core area reflect the different functions and associated objectives of the biosphere reserve zones, with a dynamic development of sustainable land-use strategies in the transition zone and nature conservation in the core area.

5 Discussion

Considering the effects of thematic resolution on landscape change and landscape pattern analysis is crucial in landscape monitoring tasks because the aggregation of thematic classes is common practice (Castilla et al. 2009; Gähler and Schiewe 2007). The impact of thematic resolution on quantitative landscape analysis can be contemplated as a form of the modifiable areal unit problem (Buyantuyev et al. 2010). Varying thematic resolutions divide the landscape into different patches, as any patch is an instance of a particular class. These units are not natural but rather human constructs that assemble the patch-mosaic model (Castilla et al. 2009; Lausch et al. 2015). In this line of argument, an inappropriate thematic resolution could lead to the "ecological fallacy" for correlation and regression analysis (Buyantuyev and Wu 2007).

The interrelation of thematic resolution and magnitude of identifiable changes in land use/land cover is explained by the high occurrence of changes within thematic classes. The higher the thematic resolution, the more changes are detected due to changes in the associated land use/land cover classes (Fig. 11). This is an obvious fact, but the magnitude of this effect, especially by employing very high thematic resolution, is remarkable (Figs. 2 to 4). Regarding very high thematic resolutions

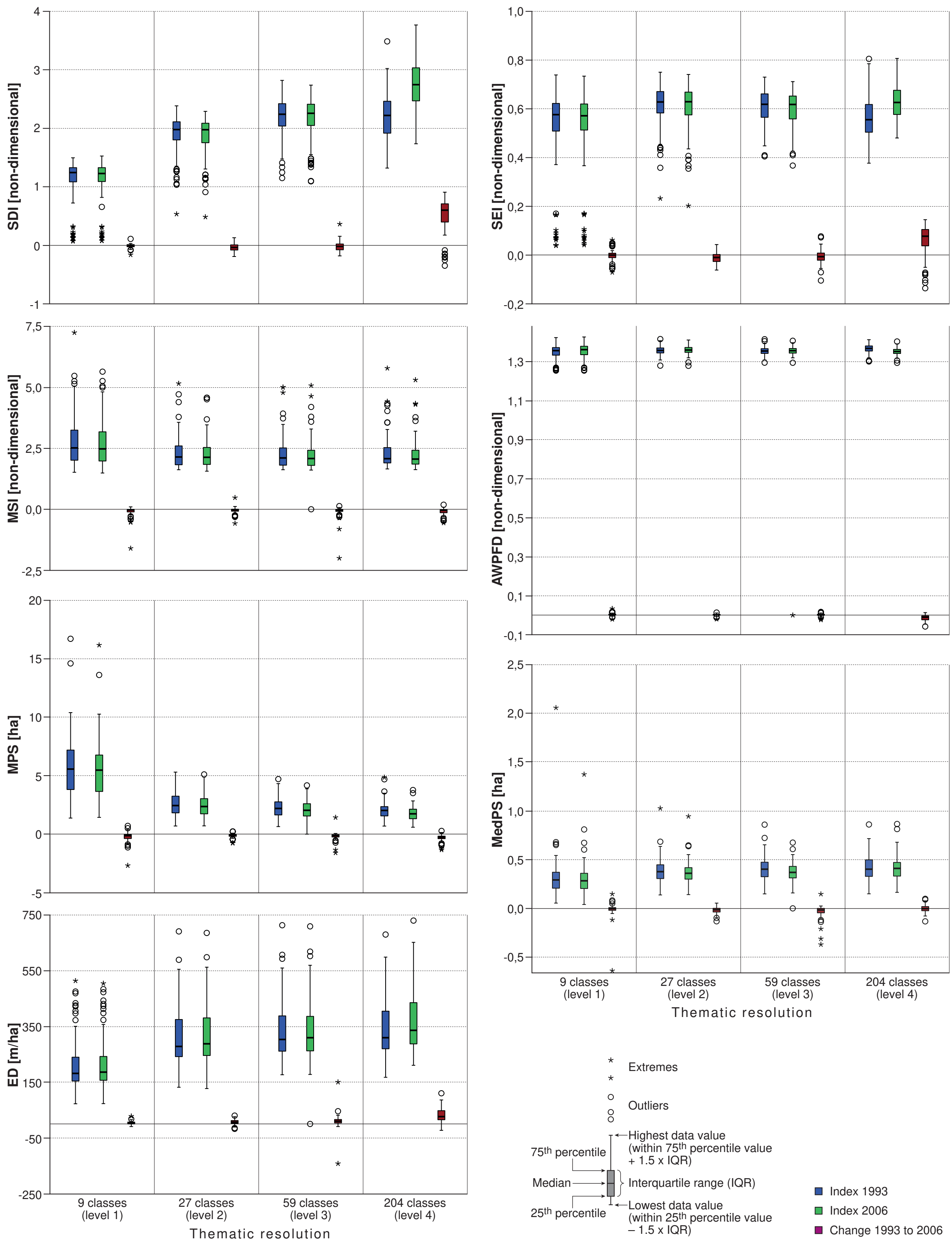

Fig. 8: Landscape metric values for 1993 and 2006 as a function of thematic resolution. Values are calculated based on the 91 administrative units within the biosphere reserve. Blue boxplots indicate index values calculated for 1993; green boxplots indicate index values calculated for 2006; changes between years for each resolution are represented by red boxplots. (SDI: Shannon diversity index, SEI: Shannon evenness index, MSI: mean shape index, AWPFD: area weighted mean patch fractal dimension, MPS: mean patch size, MedPS: median patch size, ED: edge density)

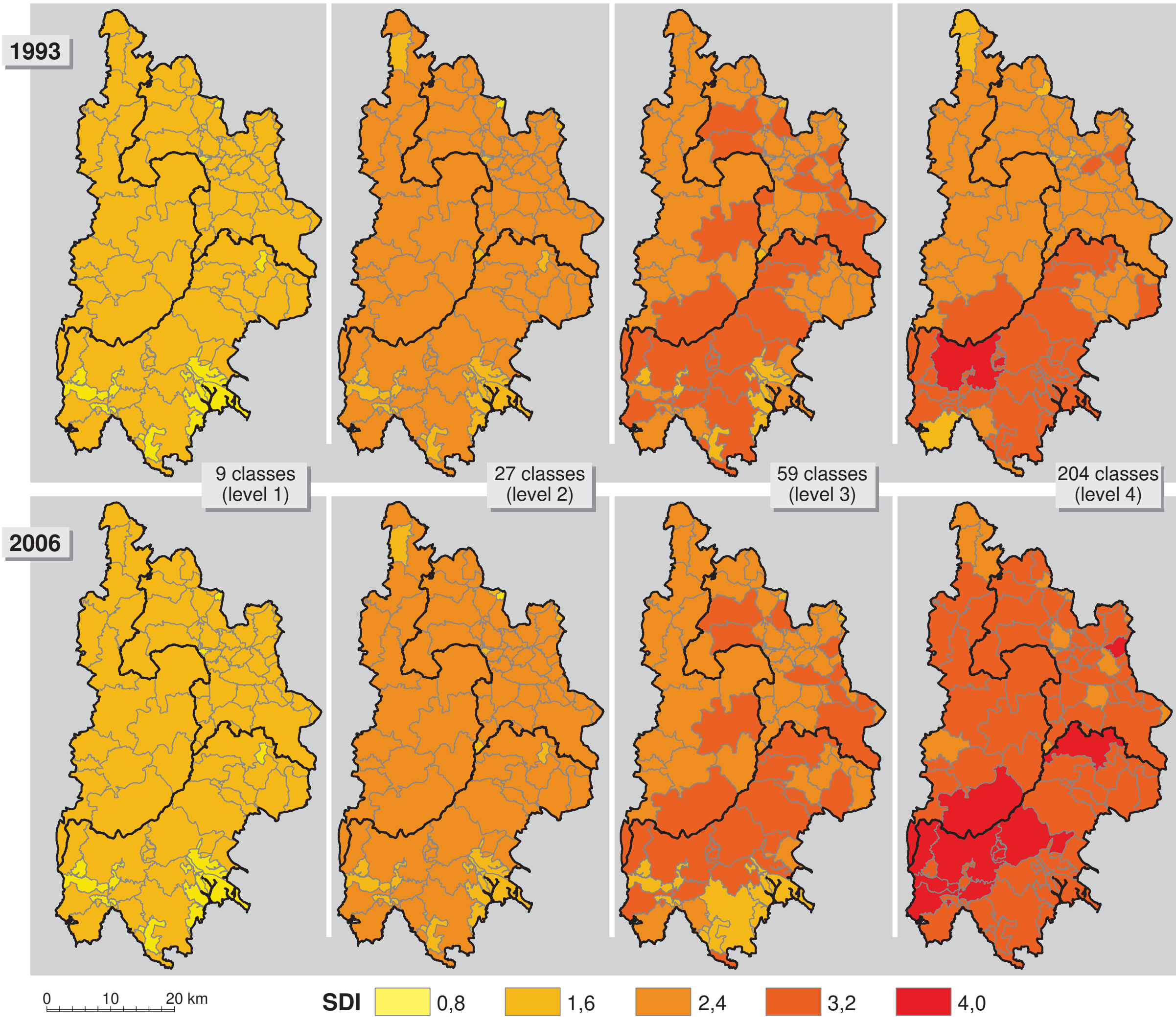

Fig. 9: SDI values calculated at the community level for different thematic resolutions. (Data sources for administrative boundaries: Bundesamt für Kartographie und Geodäsie, Frankfurt am Main, 2011, Thüringer Landesanstalt für Umwelt, Jena, Thüringer Landesvermessungsamt)

(Level 4, 204 classes), there is a risk of overestimating land cover/land use changes. For example, in many cases, it is not of concern if the secondary use of traditional orchards (Streuobstwiesen) is grassland or cropland as long as the traditional orchards are conserved. The significance of thematic resolution in landscape change analysis also was demonstrated by Pointius and Malizia (2004), who examined the effect of category aggregation on measurements of land use/land cover change based on classified raster data sets. However, comparisons of the presented results with other studies is hampered due to a lack of studies dealing with the issue of thematic resolution and the fact that most of the previous investigations are based on raster rather than vector data.

Regarding the landscape metrics, there are 3 general response patterns to changing thematic resolution: increasing, decreasing, and consistency. The results of the landscape metric calculations suggest that the values of 3 out of 7 landscape metrics are particularly influenced by thematic resolution. Buynantuyev et al. (2010) and Buynantuyev and Wu (2007) assessed the impact of thematic resolution on landscape pattern analysis using classified Landsat satellite imagery of 5 and 6 different years for a study site in Arizona. The original 12 thematic-resolution classes gradually were aggregated into 9, 6, 4, and 2 classes. As the second highest resolution in their studies equated to the lowest resolution of this study, comparisons are challenging. However, Buynantuyev and Wu (2007) found that 12 out

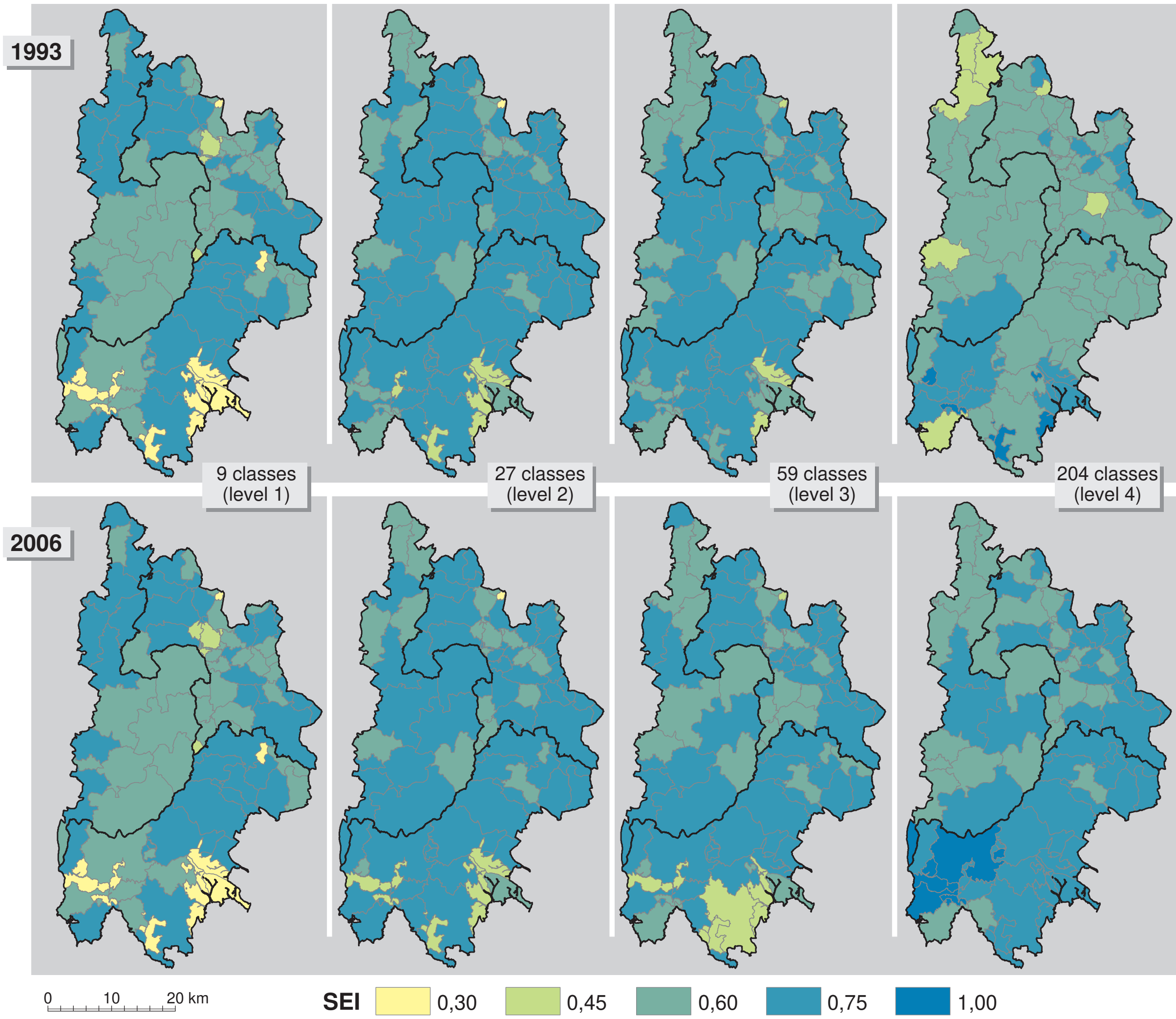

Fig. 10: SEI values calculated at the community level for different thematic resolutions. (Data sources for administrative boundaries: Bundesamt für Kartographie und Geodäsie, Frankfurt am Main, 2011, Thüringer Landesanstalt für Umwelt, Jena, Thüringer Landesvermessungsamt)

of 15 values showed distinct changes with increasing thematic resolution. The increase of landscape diversity (SDI) and edge density (ED) as a function of thematic resolution is indicated as similar to the presented results in this study. Contrariwise, the authors observed an increase of the AWPFD when the thematic resolution was increased from 2 to 12 classes, whereas AWPFD was considered to be less affected by changing thematic resolution in this study. Generally, it appears that metrics measuring shape complexity, like the fractal dimension (AWPFD) and the shape index (MSI), are less sensitive to varying classification details. Indeed, Liu et al. (2013) investigated an erratic behavior of shape metric values, but their results are based on raster data sets with a thematic resolution up to only 18 classes. The great sensitivity of mean patch size (MPS) as a metric associated with patch area and the comparatively minimal response of evenness metrics (SEI) have been stressed by Huang et al. (2006). Their study examined the responses of 24 metrics to thematic resolutions ranging from 2 to 35 classes. A comparison of the results suggests that thematic resolution may effect MPS values most profoundly at lower thematic resolutions. This is consistent with Castilla et al.'s (2009) results. In their study, an object-based classification process was applied to satellite images for 7 study sites within national parks around the world. The authors examined the effects of classification detail on the calculated patchiness of natural landscapes. The effects of 25 different thematic resolutions, ranging from 2 to 50 classes, were assessed,

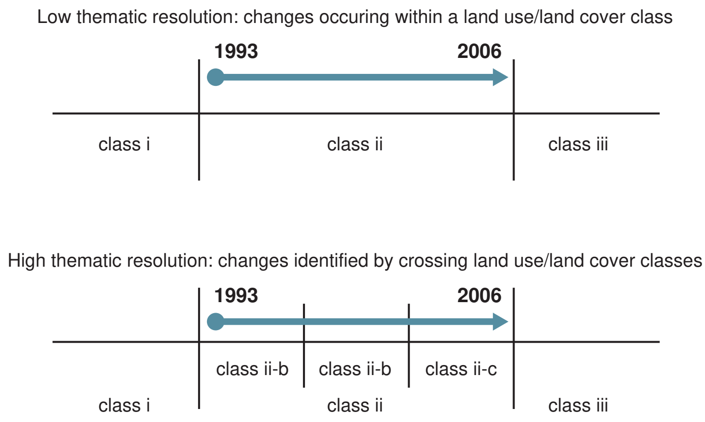

Fig. 11: Dependence of the magnitude of changes on thematic resolution. Modified after Slak and Lee 2003

and the results demonstrated that MPS values follow an inverse power law that becomes linear for more than 16 classes. These results correspond well to the observation that the effect on MPS values is clearest at low thematic resolutions and less distinct with increasing classification detail. However, different intervals of classification detail must also be considered in this respect.

Qualitative divergences regarding the behavior of landscape metrics in response to changing thematic resolution are most difficult to predict. Results at the community level show that for the landscape diversity (SDI), not only is the metric value altered as a function of classification detail but also the direction of changes differ. Conflicting results also were described by Buyantuyev et al. (2010) for the largest patch index and by Buyantuyev and Wu (2007) for the patch size standard variation but not for diversity metrics. To infer which thematic resolution is most suitable to describe actual changes of landscape patterns and to verify results of metrics that show qualitative discrepancies, field observations would be needed for comparison.

Although Lustig et al. (2015) and Townsend et al. (2009) stated that map extent is an important issue within the scope of landscape pattern analysis, though the impact of different community surface areas seems to be negligible in this study.

The investigation of the impact of classification detail on the detection of temporal landscape pattern changes in the 3 biosphere reserve zones reconcile previous findings: Effects of thematic resolution are most pronounced at very low and very high thematic resolutions. Thus, choosing which thematic resolution is appropriate depends on the monitoring objectives. Buyantuyev et al. (2010) stated that there is no single optimal thematic resolution, but the appropriate level of detail must be critically considered for a given research study. Furthermore, the thematic resolution of data sets must be consistent to allow comparisons of landscapes over time (Walz 2015).

6 Conclusion

In conclusion, the results indicate that 1) the effect of thematic resolution on the magnitude of landscape change and landscape metric values is most pronounced at low or very high thematic resolutions. Effects are moderate if intervals of classification detail are small. However, results differ significantly as a function of thematic resolution, which has to be considered when interpreting findings of quantitative landscape analysis. Unlike previous studies, the effects of very high thematic resolutions with a classification scheme comprising more than 200 classes (biotope types) are assessed without conducting a raster conversion to preserve polygon shapes. Even though there is a risk of overestimating changes of land cover/land use, there is also great potential regarding detailed landscape structure analysis; 2) landscape metrics may be critically assessed, particularly regarding qualitative effects (i.e., divergences of direction of change); and 3) there is no optimal thematic resolution to detect temporal changes of landscape patterns. Thematic resolution has to be set critically to obtain an appropriate level of detail regarding the processes of interest. Summing up the results regarding the temporal landscape pattern analyses, it should be noted that in this study, shape-related metrics, like the AWPFD and MSI, are less sensitive to changing thematic resolutions compared to area-, edge-, or diversity-related metrics. However, these metrics are most difficult to interpret. Concerning the landscape diversity metrics, the results indicated that the SEI is significantly less sensitive to different classification schemes than the SDI, which has even shown conflicting results. In consideration of the behavior of area analysis metrics, the MedPS shows a higher robustness than the MPS.

Such results are of concern in an applied context (e.g., in the context of data acquisition to monitor conservation sites such as biosphere reserves). In this respect, it is important to include that uncertainty in monitoring processes is not only of concern in data-poor regions (Lechner et al. 2012).

Future research could integrate the biotope line and point features into the polygon data set to explore a higher level of classification detail and conduct an enhanced assessment of landscape fragmentation. A further differentiation of more thematic resolution levels (different classification schemes) also could provide advanced insights and an investigation of metric behavior using contrived data and equal intervals of classification detail. Moreover, applying the same methods in other biosphere reserves representing different landscapes would yield findings regarding the feasibility and transferability of the results.

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