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Analysing the spatial structure of the Estonian landscapes: which landscape metrics are the most suitable for comparing different landscapes?

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Abstract. We calculated 15 landscape metrics on 35 Estonian landscapes and performed factor and principal component analyses in order to determine which landscape metrics work on Estonian Basic Map and which do not. The results showed that there are four main components that describe landscape structure: *dominance*, *contrast*, *shape complexity*, and *composition*. We suggest the following landscape metrics for measuring these aspects respectively: ED or SIDI, TECI or ECON_MN, SHAPE_MN, and PRD. However, the selection of the metrics always depends on the purpose of the study and the character of the ecological process. Principal component analysis also showed that heights and plains have more heterogeneous landscape than lowlands. Moreover, although the heights (Otepää and Haanja) and the plains with urban areas (Tallinn and Tartu) have high fragmentation and heterogeneity, they have different contrast values: urban areas have very low contrast while in the case of heights contrast is high.

Key words: landscape metrics, map analysis, principal component analysis.

INTRODUCTION

Spatial structure of landscapes is a central object of investigation in landscape ecology. This structure finds its expression in landscape pattern, which integrates both complex conditions of the natural environment (Quaternary cover, soil, topography, vegetation, local climate) and human-induced changes, first of all land use, the main object of human impact. Describing landscape pattern is essential in order to understand the relationships between landscape pattern and ecological processes. Therefore measurement of different parameters of spatial structure is an essential part of landscape ecology.

Within the past 30 years hundreds of landscape metrics indices have been proposed by various researchers to analyse the composition and configuration of landscape structure. Most of them are covered by the FRAGSTATS computer program (McGarigal et al., 2002). Since its emergence the measures and methods incorporated into the FRAGSTATS software have been very widely used.

In Estonia landscape metrics have been used in various studies: Roosaare (1982) applied a system of indices to analyse the landscape structure of the small island of Vormsi; Uuemaa et al. (2005) studied scale issues; Palang et al. (1998) and Aunap et al. (2006) used landscape metrics for studying landscape changes in Estonia; Uuemaa et al. (2007) examined how landscape pattern influences water quality in catchments; Mander et al. (2010) investigated the coherence of landscapes using landscape metrics; Oja et al. (2005) analysed the relationships between bird diversity and spatial heterogeneity of Estonian landscapes at different scales. Uuemaa et al. (2009) also gave an extensive overview of various uses of different landscape metrics.

There are many studies on the scale dependence of landscape metrics (Wickham & Riitters, 1995; Wu et al., 2002), correlations between landscape metrics (Cain et al., 1997; Riitters et al., 1995) and also several papers on how to interpret landscape metrics (Haines-Young & Chopping, 1996; Turner et al., 2001). However, it is not rare that landscape metrics are misused. Some metrics have theoretically a reasonable range but give actually almost constant values for all landscapes. The selection of the metrics depends first of all on the purpose of the study (mostly ecological process) and also on the landscape character.

A large number of metrics can be considered for the analysis of landscape pattern and structure. Ideally, there is a small set of metrics that span the important dimensions of pattern and structure, but which are not redundant (U.S. Environmental Protection Agency, 1994). Previous studies have attempted to determine if the major components of landscape structure can be represented by a parsimonious suite of independent metrics (e.g., McGarigal & McComb, 1995; Riitters et al., 1995; Cain et al., 1997; Griffith et al., 2000; Lausch & Herzog, 2002; Linke & Franklin, 2006; Cushman et al., 2008; Schindler et al., 2008). All these studies found that landscapes can be described by a few components, but these components were different among studies. Cushman et al. (2008) argued that different studies did not use the same pool of metrics and applied different methods to identify components but also it is possible that there are no fundamentally important aspects of landscape structure and instead structure patterns are peculiar to specific landscapes. It is more likely that different landscapes have different spatial aspects and therefore also the suitable landscape metrics vary. Besides, the maps used for analysis are different (scale, resolution, classification). Therefore it is useful to find a core set of metrics suitable for each region. Moreover, often landscape metrics are used on categorical maps of land cover/use that only reflect one theme. However, there are also some studies performed on a combination of several data sets. For example, Van Eetvelde & Antrop (2009) used DTM, CORINE Land Cover, a soil map, and a satellite image for landscape classification in Belgium, and Fasona & Omojola (2009) combined topographic data and land cover data for determining the landscape changes in Nigeria.

The aim of this study is to give an overview of the landscape metrics suitable for describing and analysing Estonian landscapes using the Estonian Basic Map based on previous experiences and factor and principal component analyses performed in the current study.

METHODS

Thirty-five study sites were selected on the basis of Estonian landscape regions so that they represent all different landscape types of Estonia (Fig. 1). Landscape regions are geosystems determined by relief forms. Thus, a region differs significantly from neighbouring areas in its geological structure (Arold, 2005). Landscape regions can be divided into six general groups: (1) accumulative heights (hereafter heights) – the most dominant relief forms are till-covered kames, the landscape is very fragmented and dominated by semi-natural grasslands and forests; (2) uplands with bedrock core (uplands) – flat-topped bedrock uplands flattened by the erosional activity of glaciers, they are characterized by cultural landscape with agricultural areas and numerous large rural settlements; (3) inter-upland depressions (depressions) – located between uplands and heights, higher areas that have washed till plains are mostly cultivated and in the lower parts there are paludified forests; (4) plains (plains) – elevated areas with flat or slightly wavy surface due to glacial abrasion, the main formations joining the relief of plains are river valleys; (5) coastal lowlands and sea islands (lowlands) – the topography is largely dominated by sandy marine plains, the landscape structure is diversified by beach ridges and the mires between them, mostly covered by forest; (6) inland paludified lowlands (lowlands) – formed the bottom of large inland waterbodies during the Late Ice Age and also in the Holocene; nowadays

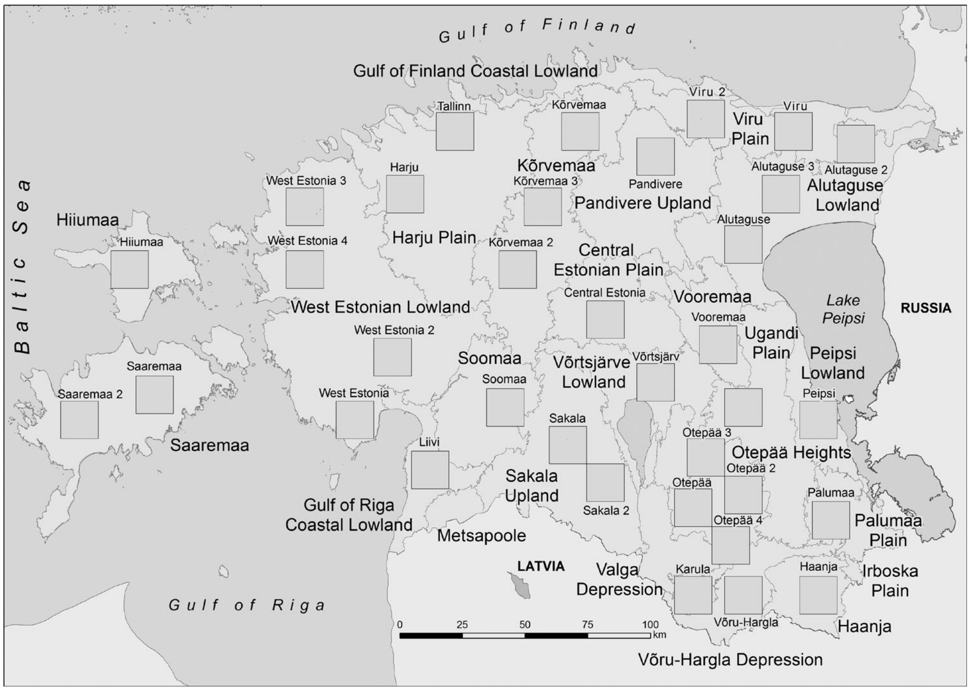

Fig. 1. Study sites and landscape regions of Estonia.

mires take up over a third of the regions' territories. The two last regions are later in principal component analysis used as one group – lowlands.

In some landscape regions, more than one study area was chosen to cover the different aspects of land use. There were sites dominated by agricultural land use, forests, bogs, mining areas, or urban areas. From four smallest landscape regions none of the study areas were chosen as they were too small to fit the study site. However, there is at least one representative study site from each six general regions. Study areas were formed on the basis of basic map sheets, i.e. each study area consisted of a 3 × 3 basic map sheet. Each study area was 15 km × 15 km (Fig. 1).

The Estonian Basic Map (1 : 10 000) was used for the calculation of metrics as the most accurate and usable map in Estonia. The classification of the Basic Map was not changed, only all the buildings were grouped as one type – 'buildings'. Therefore we used the following categories: lakes, water courses, sea, small ponds, forests, young forests, grasslands, orchards, fallow lands, cemeteries, sparsely vegetated areas, fens, raised bogs, peat fields, abandoned peat fields, bushes, arable lands, recreational open space, yards, buildings, roads. As Uuemaa et al. (2005) found that for the Estonian Basic Map the optimal pixel size is 10 m, we also used 10 m resolution for converting from vector to raster format.

Landscape metrics were calculated for all the study sites using FRAGSTATS 3.3. We calculated the following landscape metrics: (1) Edge Density (ED) – the total length of all edge segments per hectare for the landscape under consideration; (2) Patch Density (PD) – the number of patches per unit of area; (3) Mean Patch Area Distribution (AREA_MN) – the sum across all patches in the landscape of the corresponding patch areas divided by the total number of patches; (4) Mean Shape Index (SHAPE_MN) – patch level shape index averaged over all patches in the landscape; (5) Perimeter-Area Fractal Dimension (PAFRAC) – the sum across all patches 2 times the logarithm of patch perimeter (m) divided by the logarithm of patch area (m^2); (6) Contrast Weighted Edge Density (CWED) – equals the sum of the lengths (m) of each edge segment in the landscape multiplied by the corresponding contrast weight, divided by the total landscape area (m^2); (7) Total Edge Contrast Index (TECI) – equals the sum of the patch perimeter segment lengths (m) multiplied by their corresponding contrast weights, divided by total patch perimeter (m), multiplied by 100 (to convert to percentage); (8) Mean Edge Contrast Index (ECON_MN) – quantifies the average edge contrast for patches of a particular patch type (class level) or for all patches in the landscape; (9) Percentage of Like Adjacencies (PLADJ) – the proportion of cell adjacencies involving the same type; (10) Contagion (CONTAG) – indicates the aggregation of patches; (11) Patch Cohesion (COHESION) – proportional to the area-weighted mean perimeter–area ratio divided by the area-weighted mean patch shape index; (12) Patch Richness Density (PRD) – equals the number of different patch types present within the landscape boundary divided by total landscape area (m^2); (13) Shannon's Diversity Index (SHDI) – based on information theory, indicates the patch diversity in the landscape; (14) Simpson's Diversity Index (SIDI) – represents the probability that any 2 pixels selected at random would be different patch types; and (15) Simpson's Evenness Index (SIEI) − is expressed so that an even distribution of area among patch types results in maximum evenness. For details and metrics formulae see McGarigal et al. (2002).

For describing the actual range of landscape metrics on the Estonian Basic Map we used box plots and for factor analysis we used the same principles as Riitters et al. (1995) did for finding the core set of landscape metrics based on US data. As many of the metrics are very strongly correlated, some of them were immediately eliminated by performing correlation analysis. Metrics that had correlations with each other higher than 0.9 were grouped and only one metric was selected from the group. In this process we eliminated five metrics: PD, CWED, and PLADJ (the representative metric for them was ED); and SHDI and SIEI (the representative metric for them was SIDI). We preferred SIDI because its range is from 0 to 1, which makes the interpretation easier. Correlation matrix was used for factor analysis by the principal components method. It was performed in STATISTICA 7.1 (StatSoft Inc., 2005). We used varimax rotation to elucidate the underlying factors. For determining how well it is possible to describe and classify different landscape regions with the landscape metrics we also performed principal component analysis, which enables classification of the cases. We used landscape regions as grouping variable. For principal component analysis the data were normalized. The level of significance $\alpha = 0.05$ was accepted in all cases.

RESULTS AND DISCUSSION

The results of the factor analysis by the principal component method showed that the first two factors together explained 70.1% and the first four factors 87% of the variation in 10 landscape metrics (Table 1). A rule-of-thumb for retaining factors is that the associated eigenvalue be greater than one (Riitters et al., 1995). The first three factors met this criterion, and the fourth was retained because it appeared to be uniquely and strongly associated with just one of the landscape metrics (PRD). The first axis is significantly positively correlated with CONTAG and COHESION, and negatively with ED, PAFRAC, and SIDI. The axis was termed *dominance*, because CONTAG and SIDI (but also ED) measure indirectly how large patches are in the landscape and whether some of the classes are dominating in the landscape. Riitters et al. (1995) and Cushman et al. (2008) found that one of the axes correlates well with the measure of large patch dominance. From this group we suggest that ED and SIDI be used as these metrics can be most easily calculated and interpreted. The second axis was most strongly correlated with *contrast* metrics (TECI and ECON_MN). The third axis was strongly correlated with SHAPE_MN and therefore was termed *shape complexity*. Metrics that evaluate the shape of the patches have been one of the factors in most of the studies (Lausch & Herzog, 2002; Cushman et al., 2008; Schindler et al., 2008). Moreover, SHAPE_MN is a good indicator of human influence on landscapes because its value is significantly lower for areas with strong human influence as humans tend to make patches of regular shape and buildings also

Table 1. Results of the factor analysis for the first four factors. Significant values are in bold ($p < 0.05$)

	Factor number			
	1	2	3	4
Eigenvalue	5.42	1.60	1.08	0.60
Cumulative, %	54.16	70.14	80.97	87.00
	Factor loadings (after varimax rotation)			
ED	**–0.70**	–0.48	0.35	–0.09
AREA_MN	0.43	0.55	–0.64	–0.16
SHAPE_MN	0.14	0.11	**–0.96**	0.01
PAFRAC	**–0.78**	–0.21	0.09	0.01
TECI	–0.35	**–0.80**	0.34	0.16
ECON_MN	0.03	**–0.92**	0.02	0.21
CONTAG	**0.93**	0.09	–0.18	–0.11
COHESION	**0.78**	0.15	–0.35	–0.23
PRD	–0.23	–0.29	0.04	**0.90**
SIDI	**–0.87**	0.06	0.01	0.31

lower the value of this metric. The fourth axis was correlated with PRD and was termed *composition* as the PRD most clearly measures it.

Plotting the first two factors for cases in principal component analysis showed that plains with urban land use (Tallinn, Tartu, and Viru) and heights (Otepää and Haanja) are on the opposite sides on the second factor axis (Fig. 2). Both urban

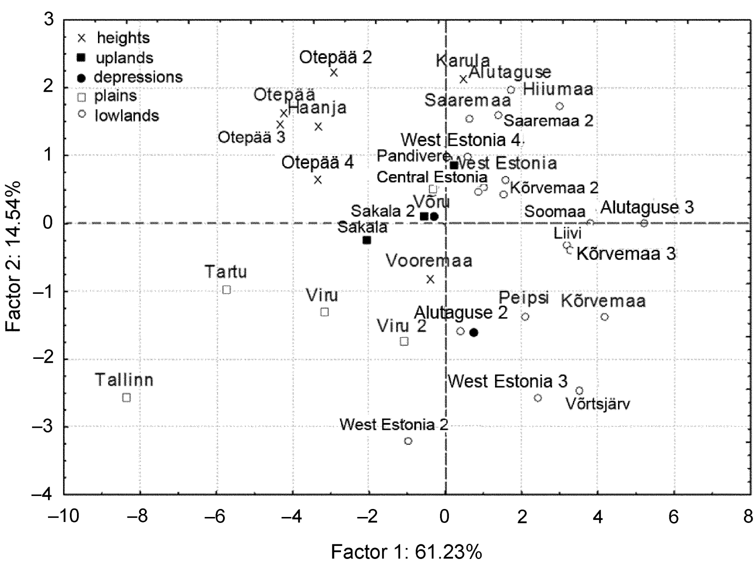

Fig. 2. Plot of the factor coordinates for the cases. Landscape regions were used as grouping variable.

landscapes and heights have a highly fragmented landscape structure and therefore it is very difficult to distinguish between them. However, contrast metrics enable making the difference as urban landscapes have a very low contrast and heights, vice versa, have a high contrast. Lowlands were on the opposite side of the first factor from plains and heights. Their landscape pattern is very homogeneous compared to heights and plains. However, uplands could not be differentiated so well. Median values and range also differed between landscape regions. For example, the ED values for lowlands were significantly lower than the ED values for plains and heights (Fig. 3). Uplands and depressions had also higher ED values than lowlands but the difference was not statistically significant.

The values of the landscape metrics depend on scale and classification. For the Estonian Basic Map the values of PD lie between 20 and 100 patches per 100 ha and the values of ED range from 50 to 250 m/ha. The theoretical range of landscape metrics is often very large but in real landscapes minimum and maximum values are never reached. For example, SHDI can theoretically range from 1 to ∞, but the actual range calculated on the Estonian Basic Map was between 1 and 3. As the theoretical range of SIDI is from 0 to 1 and the actual range is almost the same, it is better to use SIDI (Fig. 4). PRD came out of the factor analysis as it measures one of the important aspects of landscape (composition). Therefore, when using PRD it has to be taken into consideration that it has also a very small range (0.05–0.09), which means that a difference of 0.01 in PRD values may already be significant (Fig. 4).

McGarigal et al. (2002) reported that the behaviour of COHESION at the landscape level is not known. Our study confirmed this as its theoretical range is 0–100% but the actual range was 98–100% (Fig. 5). Therefore we do not recommend using COHESION at the landscape level. However, the values of

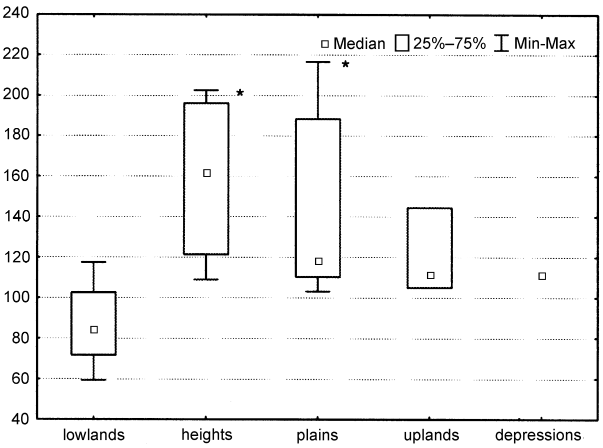

Fig. 3. Median, percentiles, and range of the edge density (ED; units: m/ha) by landscape regions. * – significant difference ($p < 0.05$) with lowlands according to the Kruskal–Wallis test.

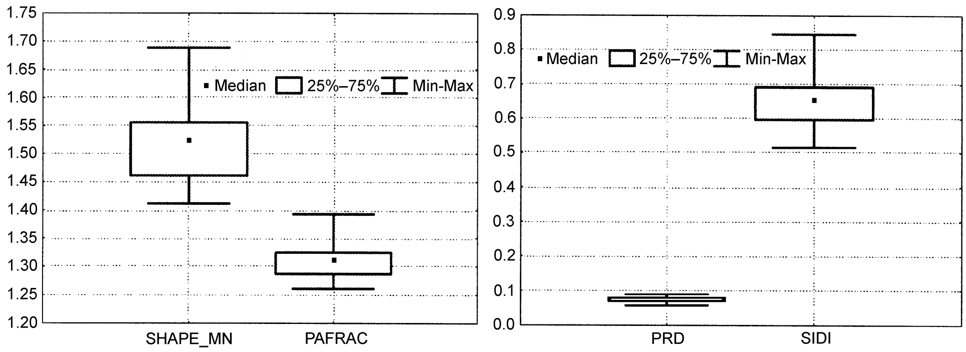

Fig. 4. Median, percentiles, and range of the shape metrics (SHAPE_MN, PAFRAC; units: none) and diversity metrics (SHDI, SIDI, SIEI; units: none).

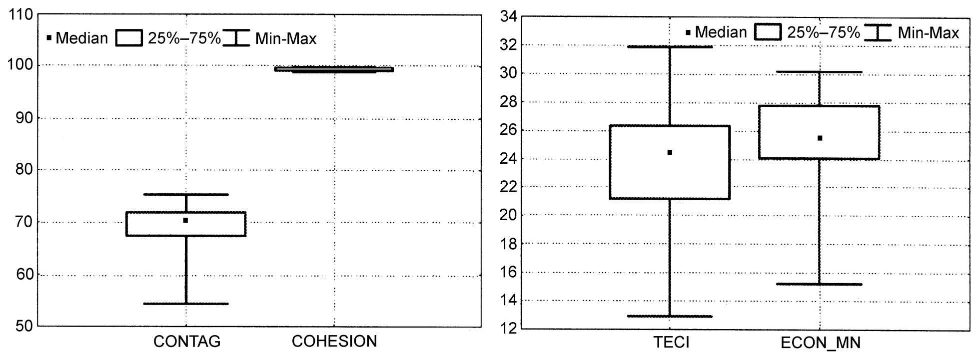

Fig. 5. Median, percentiles, and range of the contagion metrics (CONTAG, COHESION; units: %) and contrast metrics (TECI, ECON_MN; units: %).

CONTAG range from 54% to 74% and CONTAG also correlated very strongly with the first axis in factor analysis. Therefore it can be used as an indicator of dominance in Estonian landscapes.

It is most likely that for other types of maps and landscapes the dimensions would have been different but as in Estonia the Basic Map is the most accurate and commonly used map, it is useful to know the factors to measure and landscape metrics suitable for this. However, one cannot forget that the selection of metrics always depends on the purpose of the study. Landscape metrics suggested here (ED, SHAPE_MN, PRD) have been successfully used in detecting land use changes in Estonia (Aunap et al., 2006). These metrics together with contrast metrics (TECI or ECON_MN) can be used in landscape planning as indicators for detecting and predicting changes in the Estonian landscape structure. The previous studies based on the Estonian Basic Map have detected a tendency that human influence makes the landscape pattern in heights more homogeneous and in lowlands more heterogeneous, whereas the similarity between landscape patterns in lowlands and heights is increasing due to human influence (Aunap et al., 2006; Mander et al., 2010). Moreover, urban landscape pattern and expansion of urban areas are increasingly studied in the world (Uuemaa et al., 2009) and also in Estonia as suburbanization has increased very quickly in the last decade (Reimets et al., 2010). Results of this study suggest using contrast metrics when dealing with urban–rural areas.

CONCLUSIONS

We calculated 15 landscape metrics on 35 landscapes in Estonia and found in principal component analysis four landscape structure components: *dominance*, *contrast*, *shape complexity*, and *composition*. These four components cover the most important spatial aspects of landscape, and basically it is possible to evaluate the change of these aspects with only four metrics (ED, TECI, SHAPE_MN, and PRD). However, in relating landscape structure with ecological processes the selection of the metrics depends first of all on the goal of the study. As the actual range may considerably differ from the theoretical range, wrong conclusions may be drawn. We also brought out the range of the landscape metrics values for the Estonian Basic Map in order to improve interpretation in all studies related to landscape metrics performed on the Estonian Basic Map. One of the interesting outcomes of this study was that although plains with urban areas and heights had very similar landscape heterogeneity according to the landscape metrics, contrast metrics showed a significant difference between them.

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Eesti maastikumustrite analüüs: millised maastikuindeksid töötavad ja millised mitte?

Evelyn Uuemaa, Jüri Roosaare, Tõnu Oja ja Ülo Mander

Erinevatel maastikel "töötavad" erinevad indeksid ja eelkõige sõltub indeksite valik ökoloogilisest protsessist, mida uurida tahame. Käesoleva töö eesmärgiks on anda faktoranalüüsi ja seniste kasutuskogemuste põhjal ülevaade Eesti maastike kirjeldamiseks sobivatest indeksitest. Lisaks teostati ka peakomponentanalüüs, leidmaks, kui hästi maastikuindeksid erinevaid Eesti maastikutüüpe kirjeldavad.

Faktoranalüüsiks arvutati 15 maastikuindeksit 35-le maastikurajoonide järgi valitud proovialale. Maastikuindeksite arvutamiseks kasutati Eesti Põhikaarti (1 : 10 000). Lisaks toodi välja Eesti Põhikaardil kehtivad enam levinud maastikuindeksite väärtusvahemikud, mis võimaldavad indekseid paremini interpreteerida.

Esimesed kaks faktorit kirjeldasid ära 71% kogu näitajate varieeruvusest. Esimese faktoriga seondusid kõige paremini CONTAG ja COHESION (positiivne korrelatsioon) ning ED, PAFRAC ja SIDI (negatiivne korrelatsioon). Faktori koondnimetuseks pandi *domineerivus*, kuna seda maastiku aspekti mõõdavad kõik faktoriga seondunud indeksid rohkemal või vähemal määral. Teise faktoriga seondusid kõige tugevamalt TECI ja ECON_MN ning faktori koondnimetuseks sai *kontrastsus*. Kolmanda faktoriga seondus tugevalt ainult üks maastikuindeks (SHAPE_MN), mis mõõdab *eraldiste kuju keerukust*. Neljanda faktoriga tugevalt korreleerunud PRD mõõdab maastiku *kompositsiooni*. Need neli faktorit peaksid väljendama maastiku ruumilise struktuuri kõige olulisemaid aspekte. Maastikuindeksite valik sõltub alati eelkõige analüüsi eesmärgist ehk sellest, millist ökoloogilist protsessi tahetakse maastikumustriga seostada.

Peakomponentanalüüsis tulid selgelt välja ka sarnase maastikumustriga maastikud. Väga hästi eristusid teistest kuhjekõrgustikud (Otepää ja Haanja), mis on väga heterogeensed. Kõrgustikega sarnane muster oli veel tugeva inimmõjuga lavamaadel (Tartu, Tallinn ja mõlemad Ida-Viru alad), mille fragmenteeritust suurendavad hooned, kuid võrreldes kõrgustikega on nende kontrastsus väike. Tihe linnaala või linna-maa segaala on suure fragmentatsiooniga, kuid oma struktuurilt on need maastikud enamasti üsna homogeensed. Enim kasutatud maastikuindeksid eraldiste tihedus ja servatihedus ei võimalda sellist homogeensust eristada. Samas tuleb peakomponentanalüüsis erinevus dominantsuse ja kontrastsuse teljel selgelt välja.