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Multilayer landscape classification based on potential vegetation

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Abstract: Vegetation-based landscape classifications reflecting combinations of different vegetation types promote the understanding of landscape patterns and ecological restoration. However, widespread landscape classifications containing a single thematic resolution may oversimplify landscape patterns. This study aimed at providing a solution for and testing formalized landscape classification, relying on the landscape's full vegetation potential, i.e. on multiple potential vegetation (MPV). Two areas were studied: the territory of Hungary at a coarse scale and an agriculture-dominated landscape, the Körös-Maros Interfluve (south-eastern Hungary), at a fine scale. Hierarchical clustering and ordination were used to determine landscape types based on potential vegetation type composition of landscapes at each spatial scale. After cutting the resulting dendrogram at several levels and plotting the results on maps and ordination plots, the most relevant thematic resolutions were selected based on the plots and the separation of the groups was tested statistically. The vegetation-based landscape units were reasonably well aligned with biogeographical knowledge at both thematic resolution levels when the study included the whole country. Landscape unit delineation and interpretation based on the typical potential habitats linked to them benefitted from the use of a series of thematic resolutions. For example, in the case of the Körös-Maros Interfluve, apart from well-known grassland vegetation, the MPV-based approach highlighted the distribution of different landscape types and the potential for woodland in a currently non-wooded area. Furthermore, the finer thematic resolution indicated the possibility of a new landscape type along temporary small streams. The combined application of clustering and ordination enhanced the interpretation of landscape types. The use of potential vegetation as an input also enables the classification of currently transformed landscapes. The series of maps with different thematic resolutions allows a flexible choice for specific uses.

Keywords: landscape types, potential natural vegetation, potential replacement vegetation, ecological restoration

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Introduction

Vegetation-based landscape classifications delineate areas that are sufficiently uniform in terms of types of vegetation (e.g. Molnár et al. 2008, Divíšek et al. 2014) whereas vegetation maps (e.g. van der Maarel & Westhoff 1964, Bertacchi et al. 2004) are based on the species composition of vegetation types. Vegetation-based landscape classifications differ from vegetation classifications in that they result in landscape types rather than vegetation types based on species composition (such as in Botta-Dukát et al. 2005, Illyés et al. 2009, Willner et al. 2019, Novák et al. 2020). Vegetation-based landscape classifications are important for restoration (Cevallos et al. 2020) and landscape planning (Blankson & Green 1991) and also offer information that provide scientific insight.

Methods used to produce vegetation-based landscape classifications, however, are diverse. Major differences in methods lie in whether the characterization (i) was done using expert knowledge or formalized approaches, (ii) was based on actual or potential vegetation and (iii) allowed discontinuous units to be included or not. Expert knowledge-based methods typically rely on the distribution of potential natural vegetation (PNV), that is, vegetation capable of surviving under the abiotic conditions at a given date, without ongoing human management (Tüxen 1956, Supplementary Data S1). However, probably due to the expert knowledge used in these cases, the role of actual vs potential vegetation is not always separated (e.g. Molnár et al. 2008). By contrast, formalized classifications rely solely on actual vegetation (Bölöni et al. 2011a, Divíšek et al. 2014). However, PNV-based landscape characterization may also benefit greatly from formalized analyses (Cevallos et al. 2020).

Historically, PNV maps relied on expert knowledge (Tüxen 1956, Bohn 1981, Neuhäuslová et al. 2001), which naturally led to expert-based mapping when used for the delineation of vegetation-based landscape units. However, estimates of formalized PNV are also being developed (e.g. Reger et al. 2014, Somodi et al. 2017, Fischer et al. 2019), which could form the basis for formalized, PNV-based landscape classification, showing areas with uniform abiotic conditions based on the vegetation. In addition, the multiple potential natural vegetation concept (MPNV, Somodi et al. 2012, 2017) extends the original principles of PNV into a probability distribution of a set of possibly self-sustainable vegetation types at a site rather than providing a single type as does PNV. Thus MPNV, if estimated in a formalized way, includes the full vegetation potential of a landscape and provides a formalized background for mapping landscape units according to their full vegetation potential. In addition to PNV, potential replacement vegetation (PRV; Chytrý 1998) can also be presented in a probabilistic framework corresponding to MPNV. Potential replacement vegetation is also an important factor when the landscape's potential is assessed, particularly for conservation. Potential replacement vegetation is defined as self-sustainable vegetation under given climatic conditions, together with active human management. Potential replacement vegetation usually includes different vegetation types (Chytrý 1998) and has an important role in the survival of numerous flagship species (e.g. *Maculinea arion* – Casacci et al. 2011, Tartally et al. 2019; *Phengaris teleius* – Kőrösi et al. 2014; *Psophus stridulus* – Rada et al. 2017). For this reason, besides protecting existing stands, these vegetation types are also often restored (e.g. Barbaro et al. 2001, Storm et al. 2016). This underlines the fact that both PNV and PRV are relevant for assessing a landscape's potential. For the sake of simplicity, the union of PNV and PRV is referred to as potential vegetation (PV) in the remaining part of this paper. Similarly, the multilayer estimation of PV that follows the principles of MPNV is abbreviated as MPV.

Finally, it remains to decide on the contiguous/discontiguous representation of vegetation-based landscape units. Typically, spatially coherent units, i.e. regions, are delineated by regionalization processes (e.g. Molnár et al. 2008), while discontiguous units, i.e. landscape types, result from the typification of landscapes (e.g. Divíšek et al. 2014). PNV-based approaches have used contiguous units up till now, although they were parts of more complex landscape identifications, i.e. where other factors were also considered (Perko et al. 2015, Simensen et al. 2018). This is partly a natural result of expert-based delineation and partly a requirement for application even in formalized settings (Cevallos et al. 2020). On the other hand, landscape classification, when using discontiguous units, i.e. landscape typification, provides an insight into the internal similarity of landscapes (e.g. Bölöni et al. 2011a, Divíšek et al. 2014, Alcántara Manzanares & Muñoz Álvarez 2015, Perko et al. 2015).

Whichever of the three choices listed above are used in studies on landscape classification, the majority are aimed at providing one best representation (Molnár et al. 2008, Bölöni et al. 2011a, Cevallos et al. 2020). Although Divíšek et al. (2014) and Alcántara Manzanares & Muñoz Álvarez (2015) indicate that using a range of thematic resolutions (i.e. maps with different levels of detail of the landscape types/regions) can improve the insight into the region studied, they nonetheless strive for an optimal solution, while Perko et al. (2015) present two thematic resolutions of landscape regions based on different input data.

The current study has two main aims: (i) To create a formalized framework that can be applied to the potential vegetation in large regions, which yields a flexible representation of the vegetation-based classification of landscapes that reflects their vegetation potential. This involved a synthesis of the following characters of vegetation-based landscape typification: potential vegetation (PV) as a basis; formalized approach; allowing discontiguous units to reflect similarities between types; and allowing several thematic resolutions to be viewed as part of landscape classification rather than striving for an optimum. (ii) To test this framework in a region that has been highly transformed by humans and assess its potential in such a data-poor environment.

Material and methods

Data

Multiple potential vegetation (MPV) data were used to obtain the formalized multilayer, potential vegetation-based landscape classification (mPC). The MPV data consisted of the MPNV predictions implemented by Somodi et al. (2017), together with new predictions of vegetation types representing PRV (sensu Chytrý 1998). Multiple potential vegetation of Hungary was thus composed of a total of 47 vegetation types (Bölöni et al. 2011b, Supplementary Table S1). All of the predictions were calculated using the method of Somodi et al. (2017). More details are given in Supplementary Data S2.

The models included the MPV estimate of the probability of survival of (semi)natural vegetation types (Bölöni et al. 2011b, Supplementary Table S1), in each ~700 m diameter cell of a hexagonal grid covering Hungary. Gradient boosting models (GBMs; Elith et al.

2008) were used to estimate MPV by relating field-collected presence-absence data of actual vegetation (Hungarian Actual Habitat Database, MÉTA; Molnár et al. 2007, Horváth et al. 2008) to corresponding values of abiotic variables. Among the abiotic variables, those reflecting climate, soil, topography and water availability were considered.

Since the raw probability values predicted by the models are affected both by environmental factors and specific characteristics of a particular vegetation type, they are not directly comparable among each other. In order to achieve comparability, the raw probabilities must be standardized for each vegetation type (Somodi et al. 2017). A rescaling procedure was used for this purpose, resulting in an ordinal scale of five ranks (0, 1, 2, 3 and 4, indicating increasing probabilities of potential occurrence). This ensures that vegetation types with the same ranks are equally probable members of MPV in one spatial unit (Somodi et al. 2017). However, previous experience indicated that the two lowest ranks carry little information on potential presence and can effectively be regarded as absences. Therefore, in the current analyses MPV data were used as input, as a four-level variant of the above ordinal scale, by combining the two lowest ranks to reduce the noise caused by distinguishing them.

Study sites

The same procedure was followed for the whole territory of Hungary and for a smaller, highly transformed region of it at a finer resolution. The latter is the Körös-Maros Interfluve, delimited by the Fehér-Körös, Kettős-Körös, Hármas-Körös, Körös, Tisza and Maros rivers and the national boundary (Fig. 1, Mezősi 2017).

In the case of analyses covering the entire territory of Hungary, the data of the 267,813 hexagonal grid cells were aggregated to form a rectangular grid containing 25,936 cells due to limited computing capacity. The new, 2,225 × 1,652 m rectangular cells contained a maximum of 11 hexagons. For each vegetation type and each rectangular cell, the maximum of the ordinal-scale probability values was calculated using the hexagons whose centroid was covered by the rectangle. Based on the Hungarian Actual Habitat Database (Molnár et al. 2007), 74.3% of the rectangular cells contained (semi)natural vegetation. The smaller extent of the Körös-Maros Interfluve allowed the use of the original hexagon structure of MÉTA in the analyses. In this case, however, data on (semi)natural vegetation were only available for 30.3% of the total 16,861 hexagons, showing a more transformed character due mainly to agricultural use (arable fields).

Identification of landscape types

The procedure of identifying landscape types (i.e. recurrent combinations of vegetation types) consisted of the following main steps (Fig. 2): (i) classification of the spatial units according to their MPV composition, (ii) cutting the resulting dendrogram at various group numbers to provide a range of thematic resolutions, (iii) ordination of the spatial units, (iv) visual examination of dendrogram-based groupings in ordination plots and in physical space on maps, selection of the most informative similarity levels, (v) testing the significance of group centroids with PERMANOVA and the stability of the classifications using the Goodman-Kruskal's lambda coefficient.

As the input data were of an ordinal nature, both classification and ordination required a dissimilarity index adapted to this type of data. Furthermore, the data were relatively

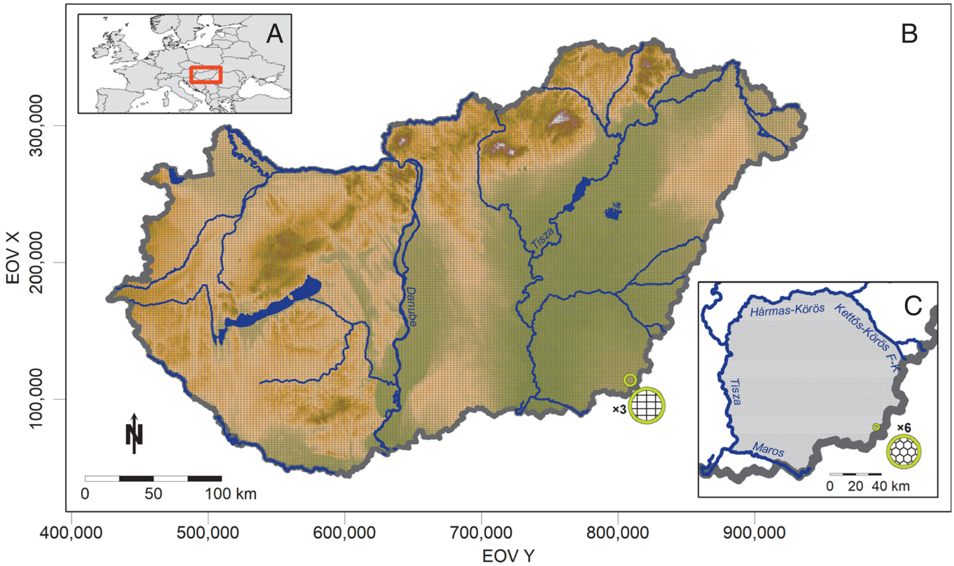

Fig. 1. Map of the two sites studied, (B) Hungary and (C) Körös-Maros Interfluve, and their location within Europe (A). The grid pattern used for the specific scale is shown in the green circles adjacent to the maps. Magnification is also indicated next to the circles. The boundary river 'Fehér-Körös' is abbreviated as 'F-K' in the subfigure (C).

rich in ties, so Kendall's τ_b (Kendall 1945) was seen as a reliable basis for the comparisons. Linear modifications were applied to the values so as to yield a dissimilarity index with values between 0 and 1:

$$d = 0.5 - 0.5 \cdot \tau_b$$

Based on the dissimilarity matrix, hierarchical clustering was performed using the unweighted pair group method with arithmetic mean (UPGMA) and the resulting dendrogram was cut at several cut-off levels. This yielded different thematic resolutions according to the number of groups (equivalent to different similarity levels). The obtained groups were projected onto maps at each cut-off.

In order to facilitate the interpretation of the groups, principal coordinate analysis was used (PCoA; Gower 1966; vegan package; Oksanen et al. 2019). To avoid negative eigenvalues, the dissimilarity matrix was square-root transformed before carrying out PCoA. The results were plotted on an ordination plot and the groupings were projected onto it. Based on expert knowledge, an interpretation of the axes and the achieved groups was also provided by plotting the arrows of the vegetation types.

After assessing the maps and the ordination plots, the most relevant group numbers, i.e. thematic resolutions, were identified using the following procedure. As a first step the smaller, new cluster (hereinafter 'new cluster') was checked to see whether it was interpretable or was a small group representing noise. To avoid overinterpretation, groups containing less than 20 spatial units were not interpreted. In the next step the ecological interpretation of both the new cluster and the remaining part were examined. Then, representative thematic resolutions were chosen from the series of maps achieved. Throughout

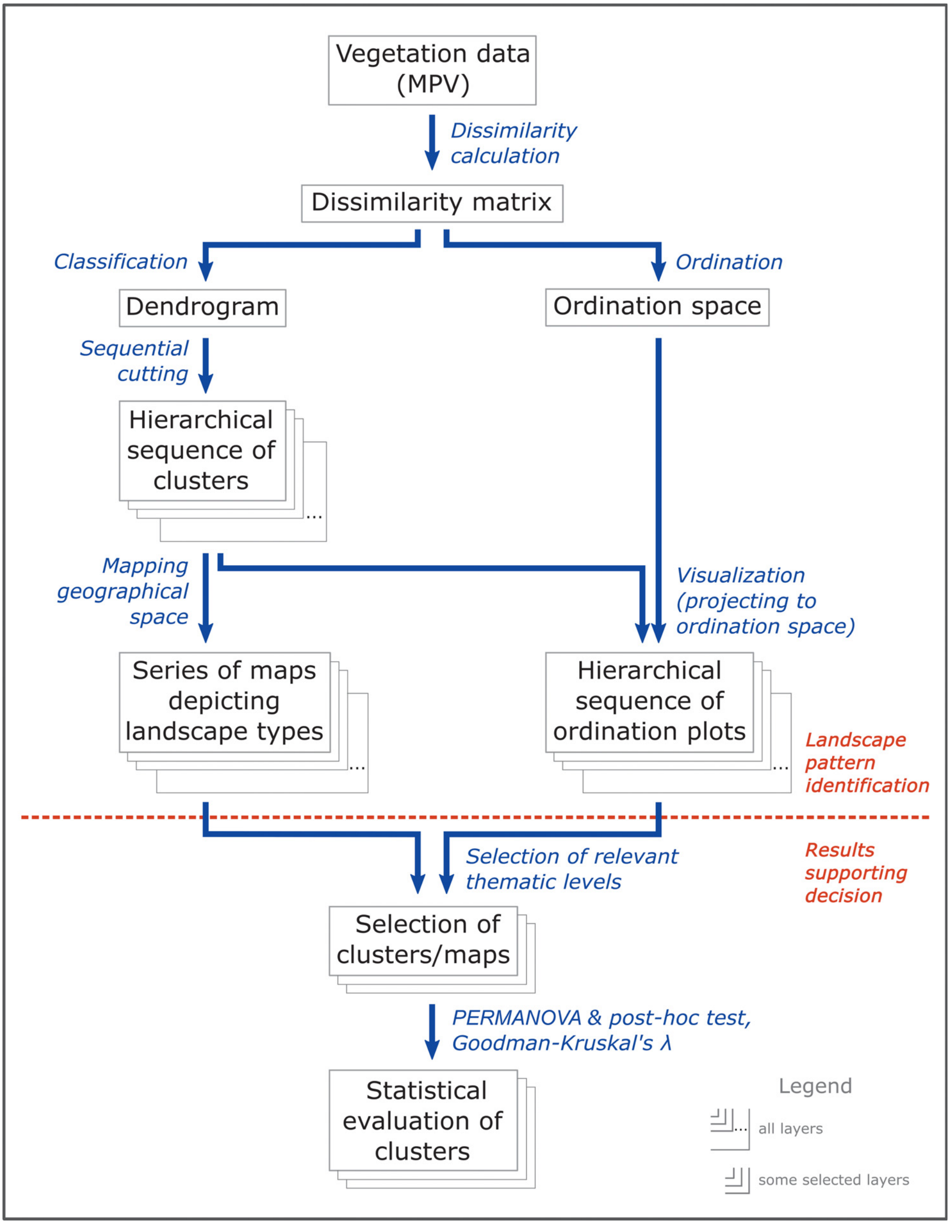

Fig. 2. Conceptual framework of the proposed landscape classification procedure.

the decision process we relied on how clearly interpretable the current new cluster and the new cluster of the next step were. The process was stopped at the stage where emerging new groups larger than sliver groups could not be satisfactorily interpreted. Finally, the classification was evaluated statistically, relying on the chosen representative thematic resolutions. First, a PERMANOVA analysis was carried out (Anderson 2001). If

PERMANOVA was significant for a specific thematic resolution, the separation of the interpretable groups was tested using a pairwise post-hoc test (RVAideMemoire package; Hervé 2020). Then, in order to test the reliability of the given thematic resolution, bootstrap samples were taken 1,000 times without replacement. The sample sizes were 10% of the original data. The classification procedure was repeated on the bootstrap samples and the dendrograms were cut to achieve the same thematic resolution (i.e. number of clusters). To compare the classification of a given bootstrap sample according to the original and the new classification procedure, Goodman-Kruskal's lambda was calculated (λ; Goodman & Kruskal 1954; DescTools package; Signorell et al. 2021). This index ranges from 0 to 1, implying minimum and maximum agreement of classifications, respectively. The stability of the classification at a given thematic resolution was estimated by averaging the λ values of the bootstrap samples.

All analyses were done in the R statistical environment (R Core Team 2020) using Hungarian National Projection (HD72/EOV; EPSG: 23700) as the coordinate reference system of the spatial data.

Comparison with an existing vegetation-based landscape classification

In order to assess the relevance of mPC, it was compared with the existing single-layer, hybrid (based mainly on actual but secondarily on potential vegetation) landscape classification defined by experts (sHC; Molnár et al. 2008). This classification contains only spatially distinct regions.

Due to resolution constraints, the comparison was only possible for the country-scale analysis. For each region of the sHC, we examined how homogeneous the mPC was within that polygon. Homogeneity was measured as the percentage cover of the dominant mPC cluster (i.e. the cluster with the largest area within that polygon).

Results

Whole-country analysis

In the case of Hungary, the last cut-off examined was the 15-group arrangement and the 8- and 15-group arrangements were found to be particularly informative. The dendrogram cut at these two cut-off points is shown in Fig. 3. In the 8-group arrangement six interpretable and two sliver groups emerged, the latter being too small to interpret (included less than 20 spatial base units). In the 15-group arrangement these numbers were nine and six, respectively. However, the order of emergence of the groups gave further new insights. Thus, examining the range of meaningful thematic resolutions in full had additional value. If the coarsest meaningful grouping, the 4-group arrangement was considered, the country split into three main clusters: lowland (mPC cluster 01), colline & foothill (mPC cluster 02) and low mountain (Hungary has no high mountains; mPC cluster 04) landscape types. At the next stage, first mPC cluster 05 and then cluster 07 separated from the lowland type, and are dominated by wet and sandy types, respectively (Fig. 3). mPC cluster 08, which separated from the colline & foothill type, revealed the area optimal for dry and semi-dry forest-grassland mosaics. The next interpretable cluster was mPC cluster 11, which separated from the lowland type and is a combination of gallery forests and

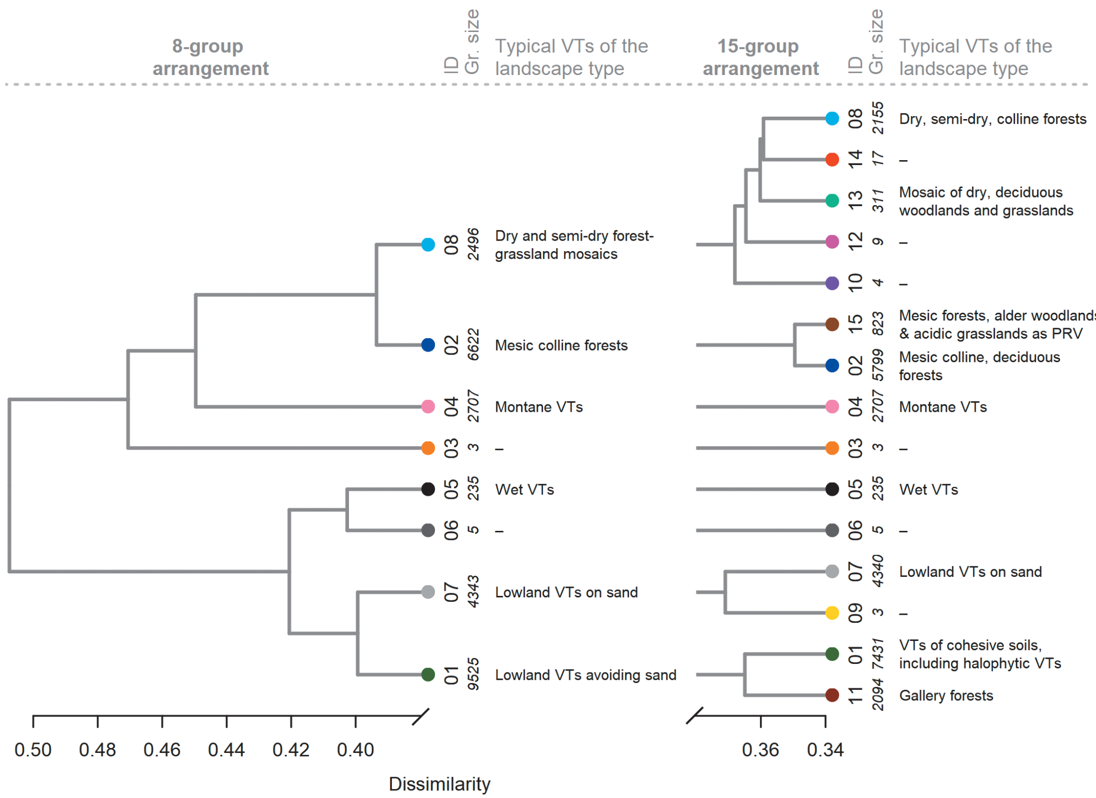

Fig. 3. Dendrogram of the landscape units of Hungary cut at two levels forming an 8-group (left side) and a 15-group landscape classification (right side). The ID of the group, the number of spatial units it contains (Gr.size) and the dominant vegetation types (VTs) are provided to help the interpretation at both classification levels. Non-interpretable groups are marked with a dash.

other types of riverine vegetation. mPC cluster 13, which separated from mPC cluster 08, is the optimal area for mosaic of dry, deciduous woodlands and grasslands. The final meaningful cluster was mPC cluster 15, which separated from the colline & foothill landscape type and includes landscapes typically hosting mesic forests, and alder woodlands together with acidic grasslands representing PRV. Though the Őrség region is geographically distant from the Külső-Somogy and Zselic landscapes (for the location of the geographic regions see Fig. 5A), this cluster links them.

The first two axes of PCoA (Fig. 4A) together explained 37.4% of the total variance (24.1% and 13.3%, respectively). The axes could be linked to topography (decreasing altitude, with increasing values along the 1st axis) and hydrology (increasing distance to water bodies, with increasing values along the 2nd axis). The interpretation of the groups is given in Fig. 3, while the maps (Fig. 4B) show their spatial arrangement. The 8- and 15-group resolutions were again used for further statistical analyses. The results of the PERMANOVA analyses were significant ($P < 0.05$) for both the 8- and 15-group arrangements, and all results obtained from the pairwise post-hoc tests were also significant (Bonferroni corrected P-values < 0.05). The estimation of the stability of the thematic

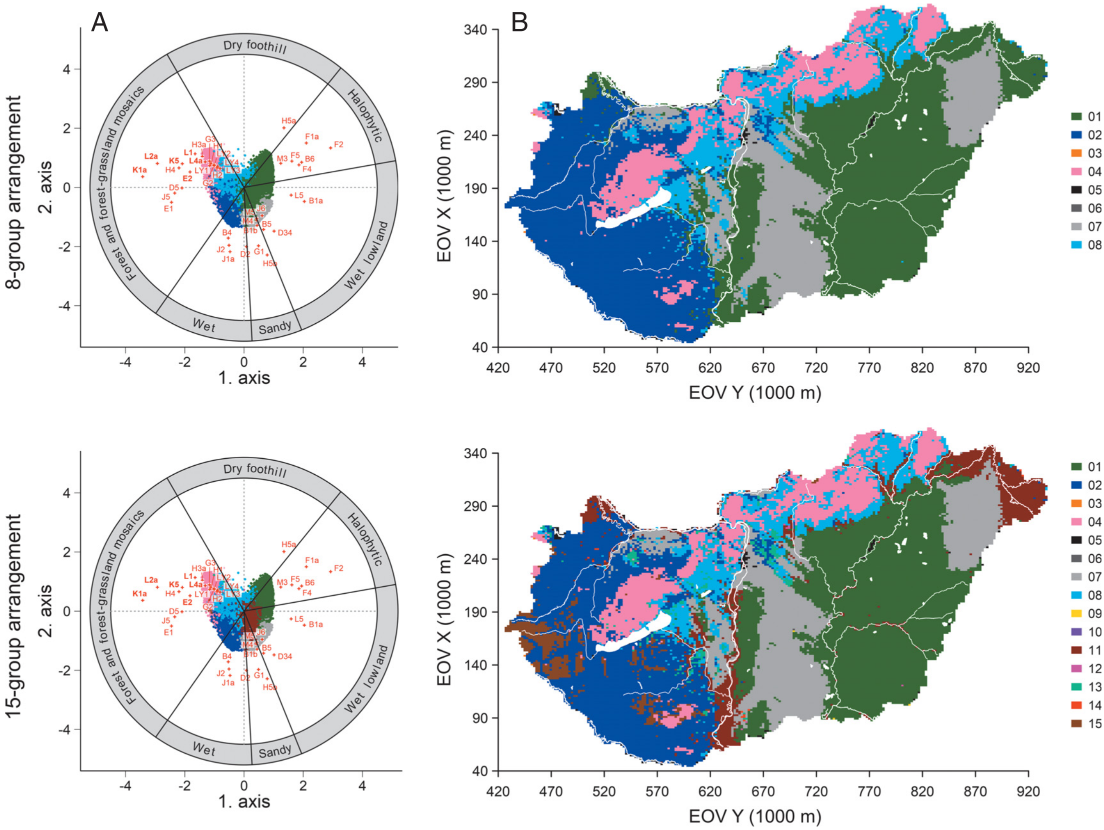

Fig. 4. (A) Ordination plots and (B) spatial arrangement of MPV-based landscape types in Hungary at two thematic resolutions (8-group landscape classification – left side; 15-group landscape classification – right side). The 1st ordination axis can be linked to topography (decreasing altitude, with increasing values along the axis) and the 2nd axis to hydrology (increasing distance to water bodies, with increasing values along the axis). The codes of the vegetation types that are at least a unit distance from the origin are shown. Codes of merged vegetation types are given in bold. For explanation of the codes of vegetation types, see Supplementary Table S1.

resolutions resulted in $\lambda_8 = 0.667$ and $\lambda_{15} = 0.695$, for the 8- and 15-group resolutions, respectively.

When comparing mPC and sHC, most of the sHC regions were homogeneously covered by specific mPC clusters (i.e. with coverage >70%) at both cut off levels (Fig. 5B-C, Table 1). It is noteworthy that two regions covered by areas optimal for gallery forests, the Alsó-Duna-völgy and Bereg–Szatmári-sík regions, were found to be homogeneous at both levels in spite of the fact that they belonged to different clusters at the finer resolution. On the other hand, a few landscapes were found to be heterogeneous at both levels (e.g. Kelet-Mezőföld, Sárvíz és Sió-völgy, Gödöllői-dombvidék). A major difference between the two levels was caused by the separation of mPC cluster 15 in the western part of the country due to mPC having more precise patterns inside the respective sHC regions (e.g. Zalai-dombság, Zselic).

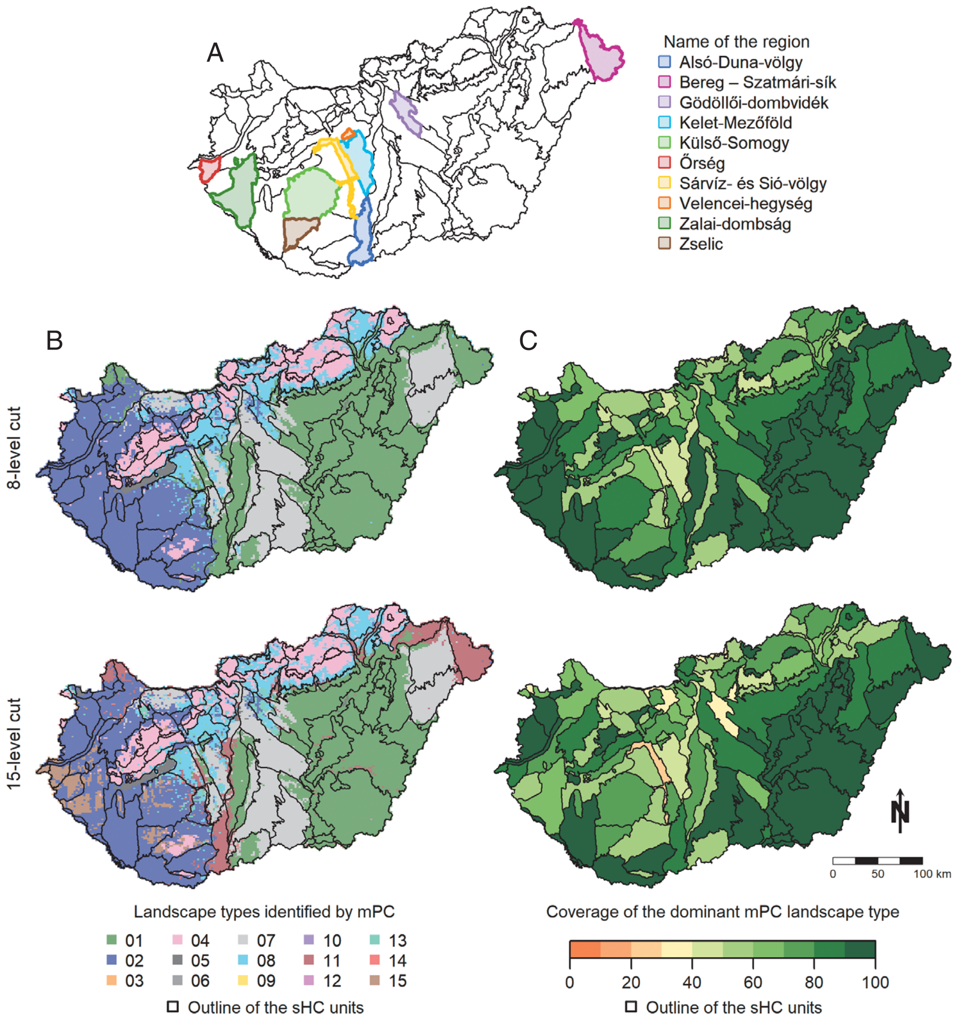

Fig. 5. (A) Location of the regions mentioned in the main text; and (B–C) comparison of the present classification (mPC) at two thematic resolutions (8-group classification – top; 15-group landscape classification – bottom) with that of Molnár et al. 2008 (sHC). In subfigure B, sHC is projected onto mPC. Subfigure C reflects the internal homogeneity of mPC inside each single sHC region based on the percentage cover of the dominant landscape type.

Detailed analysis of the small study area

In the case of the Körös-Maros Interfluve, the 7- and 11-group arrangements were found to be relevant. Fig. 6 shows the interpretation of the clusters and Fig. 7B their spatial arrangement. The mPC cluster 01 includes the area optimal for the fine scale (< 700m) mosaic of halophytic and loess grasslands. mPC clusters 02 and 03 represent areas optimal for wet, non-halophytic and wet, halophytic types, respectively, while mPC cluster 04 the area dominated by gallery forests and other riverine vegetation. mPC clusters 06 and 07

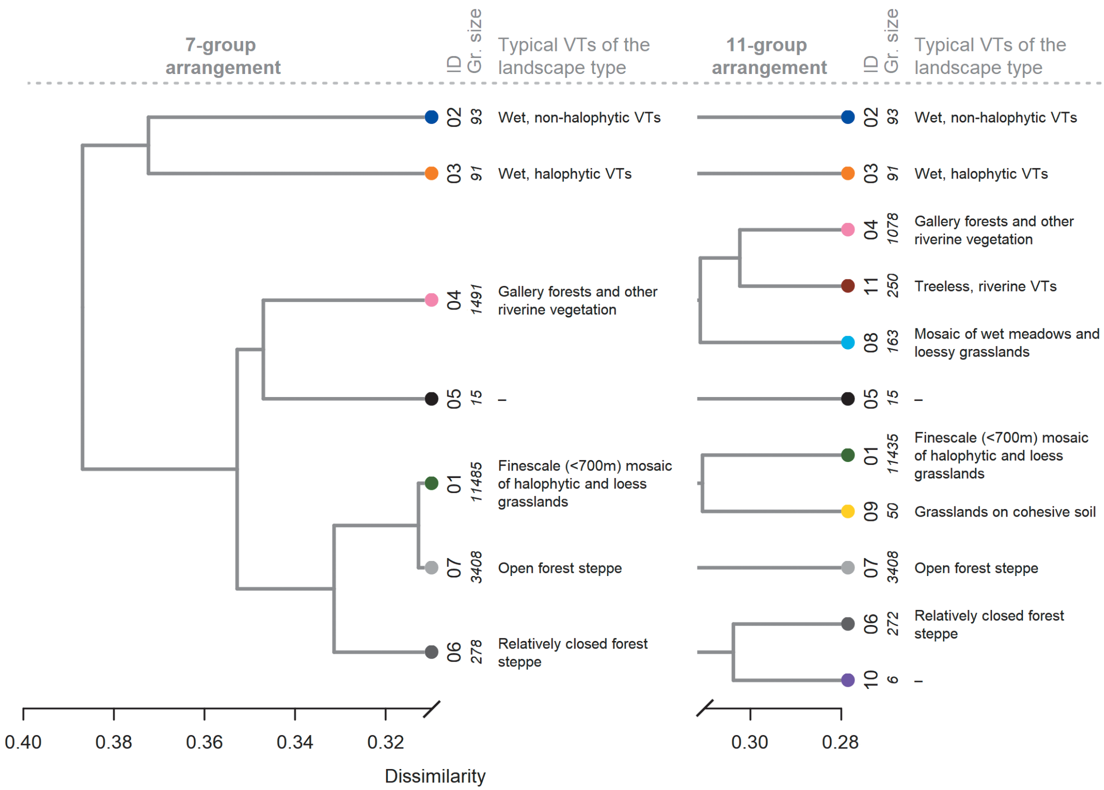

Fig. 6. Dendrogram of the landscape units in the Körös-Maros Interfluve cut at two levels forming a 7-group (left side) and an 11-group landscape classification (right side). The ID of the group, the number of spatial units it contains (Gr.size) and the dominant vegetation types (VTs) are provided to help with the interpretation at both classification levels. Non-interpretable groups are marked with a dash.

represent relatively closed forest steppe and open forest steppe dominated landscape types, respectively, and mPC cluster 08 the area optimal for mosaics of wet meadows and loess grasslands. The mPC cluster 09 represents areas dominated by grasslands on cohesive soils, while mPC cluster 11 the treeless landscape type, dominated by riverine vegetation.

The first two axes of PCoA (Fig. 7A) together explained 32.6% of the total variance (20.1% and 12.5%, respectively). The 1st axis was mainly associated with soil (increasing salinity, with increasing values along the axis, except for one outlier: saline steppe forests; M3) and the 2nd axis to hydrology (decreasing wetness, with increasing values along the axis).

The 7- and 11-group resolutions were relied on for further statistical analysis. The PERMANOVA analysis revealed significant separation between the groups ($P < 0.05$) and all the pairwise comparisons in the post-hoc test differed significantly (Bonferroni corrected P values < 0.05). The estimate of the stability of the thematic resolutions was characterized by $\lambda_7 = 0.264$ and $\lambda_{11} = 0.383$, for the 7- and 11-group resolutions, respectively.

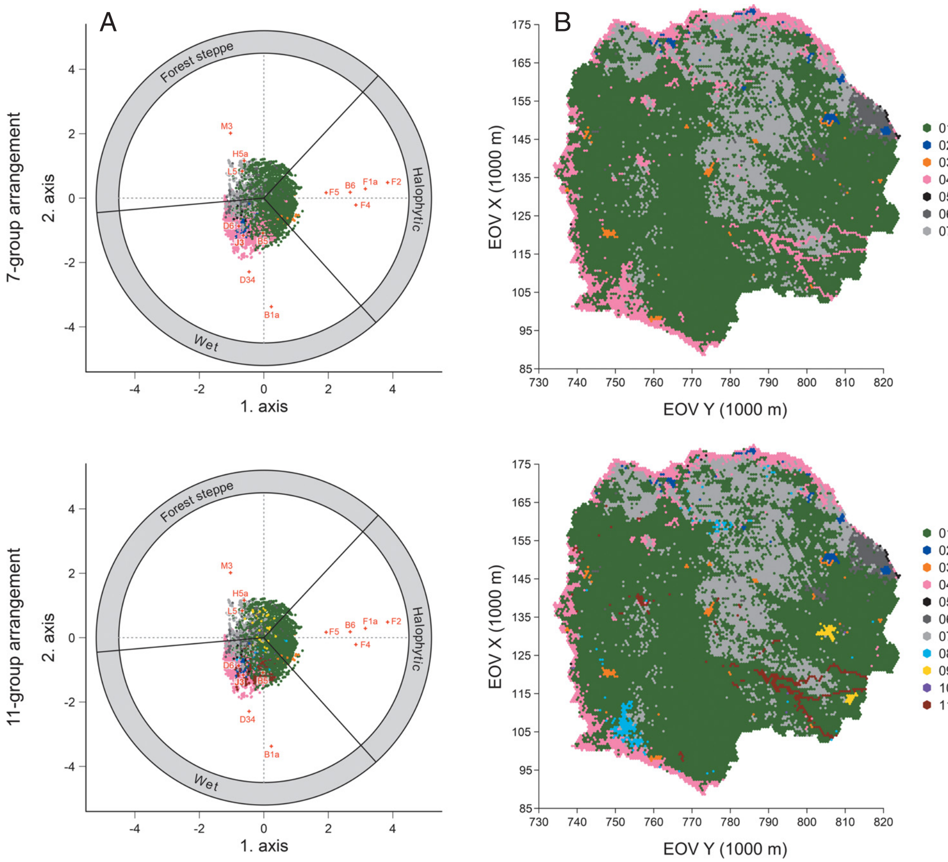

Fig. 7. (A) Ordination plot and (B) spatial arrangement of MPV-based landscape types in the Körös-Maros Interfluve at two thematic resolutions (7-group landscape classification – left side; 11-group landscape classification – right side). The 1st ordination axis was most closely connected to soil features (increasing salinity, with increasing values along the axis, except for an outlier: saline steppe grasslands) and the 2nd axis to hydrology (decreasing wetness, with increasing values along the axis). The codes for the vegetation types that are at least a unit distance from the origin are shown. Codes of merged vegetation types are in bold. For the explanation of the codes for the vegetation types, see Supplementary Table S1.

Table 1. Comparison of the present classification (mPC) with that of Molnár et al. 2008 (sHC). The degree of homogeneity was calculated as the percentage covered by the dominant mPC cluster within each single region of sHC. For the spatial distribution of the homogeneity, see Fig. 5.

Degree of homogeneity: mPC vs sHC	Percentage of hexagons occupied by the homogeneity category	
	8-group arrangement	15-group arrangement
0.20–0.29	0%	0.7%
0.30–0.39	0%	1.7%
0.40–0.49	4.6%	3.5%
0.50–0.59	9.9%	15.6%
0.60–0.69	8.8%	8.5%
0.70–0.79	7.7%	14.6%
0.80–0.89	22.1%	17.9%
0.90–0.99	39.2%	33.3%
1.00	7.7%	4.1%

Discussion

Methodological framework

The simultaneous application of a hierarchical classification and ordination is reported to facilitate the exploration of landscapes, by defining distinct groups and plotting them in contiguous space (Legendre & Legendre 1998, Urban et al. 2002). Besides enabling repeatability, they are able to reveal complex patterns and internal similarity in the structures of the main groups, so they were used in several previous studies together (e.g. Monjeau et al. 1998, Jobin et al. 2003, van Etten & Fox 2004, Blasi et al. 2007, Chuman & Romportl 2010, Fried et al. 2017). The present results support these findings and extend them by viewing the classification at multiple levels. As a single-layer, thematic map of complex vegetation patterns might be an oversimplified representation of the landscape (Strand 2011), several studies proposed a hierarchical framework (e.g. Haase 1989, Klijn & de Haes 1994) or delineated landscape units by analysing their data at multiple levels (e.g. Divíšek et al. 2014, Alcántara Manzanares & Muñoz Álvarez 2015, Perko et al. 2015, etc.). Multilayer analysis can be especially beneficial for complex (Grondin et al. 2014) or extremely diverse landscapes (Blasi et al. 2011, Perko & Ciglič 2020). In the present case, the identification of landscape types also greatly benefitted from studying several levels of detail, rather than seeking and limiting interpretation to an optimal level. For instance, in the case of the Körös-Maros Interfluve, mPC cluster 04 represents landscapes with wetlands. However, mPC cluster 11, recorded at the fine thematic resolution, revealed landscapes with temporary small streams (e.g. Királyhegyesi-Száraz-ér, Kutas-éri-csatorna, Cigányka-ér) with a different vegetation potential compared to the remaining part of mPC cluster 04, i.e. the landscape type dominated by riverine vegetation. In common with the series of maps constructed for the delineation of complex, ecological regions using a hierarchical framework (e.g. Blasi et al. 2011, 2014, Grondin et al. 2014), the varying degrees of resolution in the present maps allowed a choice of thematic resolution for specific applications. The classification process aimed at a formalized result with the possibility of multiple interpretations. However, the role of the expert remains crucial for the interpretation of the resulting groups and for determining application goals. Thus, the series of maps was based on multivariate statistical methods, while the choice of the relevant levels is an expert-dependent step. In this way, the most suitable level of detail can be selected to meet specific planning objectives (Blasi et al. 2011).

Landscape types based on cutting the dendrogram provided valuable insights into the similarity of the structure of the main landscape types. Information was gained, for instance, showing that both the area optimal for wet vegetation types (mPC cluster 05) and the gallery forest-dominated landscape type (mPC cluster 15) belonged to the main group of lowland landscape types. This approach was therefore also able to reveal the similarity of the landscape regions Bereg–Szatmári-sík and Alsó-Duna-völgy, which would not have been revealed using a contiguous region design (Molnár et al. 2008, Cevallos et al. 2020). Besides landscape characterization, another approach to landscape classification is regionalization, i.e. dividing the whole area into spatially coherent regions (Makhzoumi & Pungetti 2003). While the former approach searches for characteristic landscapes types, the latter seeks for borders that divide spatially homogeneous areas. In some cases (e.g. delimiting seed transfer zones) spatially cohesive, contiguous landscape units are required e.g. due to landscape management objectives. Based on

MPNV, such regions can be delineated in the case of Hungary (Cevallos et al. 2020). In most cases, however, applying spatial constraints during landscape classification is arbitrary and unjustified. Even seed transfer zones for ecological restoration may benefit from the discontiguous approach. The present landscape classification reveals internal similarity, which is important for seed transfer zones, as the use of propagules adapted to similar environments is likely to increase the restoration success (Mijnsbrugge et al. 2010). However, sliver clusters containing too few spatial units to attribute meaning to also emerged. The UPGMA clustering method is prown to identify outliers (Tichý et al. 2010), which are represented by the sliver groups

Using potential vegetation as a basis of classification also had specific advantages. The actual vegetation-based landscape types of Hungary published by Bölöni et al. (2011a) reveal a great number of data-deficient areas. Transformed and/or data-deficient landscapes are a frequently encountered problem in classifying landscapes into types (e.g. Molnár et al. 2008, Divíšek et al. 2014). In such situations, the classification process may be difficult if it is based solely on actual vegetation. This may hamper the process and indicate it needs to be complemented by other types of data (Chuman & Romportl 2010). However, PV-based landscape classifications are able to handle these problems, since PV can be estimated on the basis of the distribution of different vegetation types in less data-poor regions as PV-based landscape units reflect the area optimal for specific combinations of different vegetation types. This advantage is reflected in the expert-estimated vegetation-based landscape regions in Hungary (sHC, Molnár et al. 2008), where actual vegetation-based observations were complemented with expert assessment of the potential natural vegetation in areas where actual vegetation was scarce. Furthermore, actual vegetation-based landscape regions are aimed at representing the complex vegetation patterns in a single layer, an approach that may not be feasible due to information loss, as pointed also out by Strand (2011).

However, one limitation of this approach is that there needs to be a reliable estimate of PV, but this does not have to be model-based. This approach is suitable for PV estimates based on both expert and statistical methods, as well as for PVs that depict a single vegetation type per location and also probabilistic estimates of MPV. However, if only single layer PV is available, a coarser grain size should be chosen for the classification than that of the original PV in order to be able to explore recurrent combinations of vegetation types. In addition, PV may inherently contain a degree of uncertainty, which is inherited by landscape classifications based on PV.

Average Goodman-Kruskal's λ calculated on the basis of resampled and reclassified data is a useful method for evaluating the stability of the original classification (Tichý et al. 2011, e.g. Růsiňa et al. 2013, Vymazalová et al. 2016, Lengyel et al. 2018). The use of this method enabled the recognition of a certain degree of uncertainty in the present classification. Rather small average λ values recorded in the case of the Körös-Maros Interfluve indicate a high degree of uncertainty (Tichý et al. 2011). Another challenge for this method was how to handle the spatial units in sliver groups. They should not be interpreted alone, but if spatially complete mapping is the goal, a value needs to be assigned to them. A possible solution is to join them to another group, for which various approaches are possible (e.g. joining to the closest mother group) and other decisions are needed.

Subdivision of the whole country

There is a similar, but actual vegetation-based classification for Hungary by Bölöni et al. (2011a), which provides an important comparison for the present results. However, due to the different spatial units (rectangle vs rosette) only a qualitative comparison is possible. These authors also used the method of dendrogram cutting, so non-interpretable clusters also emerged in their case. In contrast to the methods used in the current analyses, they selected the optimal number of groups. In their results, the forest- and grassland-dominated landscape types were separated first, while in the present study the major dissimilarity was recorded between the lowland landscape and other types (i.e. colline, foothill and low mountain landscape types). One possible explanation of this ambiguity is that the actual vegetation is mainly grassland in lowland, so considering only actual vegetation led to the apparent result of a forest/grassland distinction. In this sense the new approach clarified the situation, since even if a potential forest presence is considered, the main difference is between hilly and lowland landscapes. Another interesting phenomenon is related to the riverine landscape type: mPC cluster 11 occurs in a far wider area along rivers than the similar landscape type defined by Bölöni et al. (2011a).

For Hungary, there is a vegetation-based regionalization (Molnár et al. 2008), sHC, which provides valuable information, since their regions were based on vegetation and local knowledge of experts. A detailed comparison of mPC and sHC revealed that mPC was homogeneous in the majority of the sHC polygons. However, the heterogeneity recorded for other regions may have had several causes. Firstly, since there is a trade-off between spatial and internal homogeneity, spatially cohesive units have lower internal similarity (Divíšek et al. 2014). Secondly, there are landscapes in sHC that embody special, transitional zones (e.g. the Külső-Somogy and Gödöllői-dombvidék landscapes), while others have unique, extremely mosaic vegetation (e.g. Velencei-hegység). Thirdly, the actual vegetation also reflects landscape history and the effects of human activity (Bailey 2004, Rašín & Chromý 2010, Batáry et al. 2017), e.g. the clearance of the loess steppes (Biró et al. 2018). Potential vegetation, however, reflects the current physical environment in terms of vegetation (Somodi et al. 2021). Thus, potential and actual vegetation-based landscape regions may reveal different characteristics for the same area.

Detailed characterization of data-deficient areas

Typically, landscape units are identified at one spatial scale, e.g. Czech Republic (Chuman & Romportl 2010), Huelva, Spain (Alcántara Manzanares & Muñoz Álvarez 2015), Saxony, Germany (Bastian 2000). It was found that zooming into subregions by means of detailed classification can provide further insightful information. Most interpretable mPC clusters in the 7-group arrangement corresponded to actual vegetation-based landscape types delineated by Bölöni et al. (2011a). For example, mPC cluster 06 included patches of the landscape type dominated by remnant steppe oak forest identified by Bölöni et al. (2011a). On the other hand, the actual vegetation-based landscape classification revealed more detail of riverine landscape types. The union of three landscape types corresponded to mPC cluster 03, which is dominated by riverine forests along lowland rivers and on floodplains, another dominated by wet meadows and marshes, and a third characterized by willow-poplar forests along rivers. Furthermore, mPC cluster 01 largely corresponded to the union of four landscape types identified by Bölöni et al. (2011a), one dominated by dry, primary or secondary saline grasslands, another by more mesic saline steppes, a third by degraded dry grasslands and a fourth by loess steppes. However, all the actual vegetation-based landscape types described above are rather fragmented as a result of human activity. In addition, mPC cluster 07 was not included among the actual vegetation-based landscape types reported by Bölöni et al. (2011a). Switching to the more detailed level, it was also striking that mPC cluster 11 exhibited a fine-scale pattern, even though it did not have a corresponding actual vegetation-based landscape type (Bölöni et al. 2011a).

The present approach provides a solution to the problem that arises when highly transformed areas occur within study areas. Other solutions, i.e. giving up the categorization of these areas (e.g. Bölöni et al. 2011a), or mixing potential and actual vegetation (e.g. Molnár et al. 2008), provide less detail for these areas and may hamper later applications. It is typical, for example, that forests are selectively removed from an agricultural landscape (Abdullah & Hezri 2008, Leblois et al. 2017, Curtis et al. 2018), as in the case of the Körös-Maros Interfluve (Molnár et al. 2012). If landscape-scale actions involving forest restoration or tree planting are considered, which is particularly relevant due to the increase in atmospheric CO_2 levels (Ciccarese et al. 2012, Bernal et al. 2018, Lewis et al. 2019), it is crucial that landscape units should reflect the sustainable potential forest cover and forest type combinations suitable for the environmental conditions. For the same reason, in any general decision-support study it is advantageous to rely on PV-based units, as failing to do so would mean the loss of an important hidden aspect of landscape character.

The current approach not only allows the seamless integration of these areas into coarser-scale classifications, but also the identification of units within transformed areas, showing the suitability of the landscape for particular vegetation types. Thus, PV-based units may be beneficial for urban planners as well, as demonstrated by Miyawaki (1998) and Capotorti et al. (2019), who relied on PV for urban greening.

Conclusions

This study outlines a hierarchical, multilayer, potential vegetation-based landscape classification framework. It offers increased insight into the vegetation potential of landscapes, by seamlessly integrating transformed and pristine areas. The multilayer formalized framework provides an insight into a range of informative levels of similarity between landscape units, and allows nested relationships between units to be explored. This approach could be particularly effective in transformed areas since, due to the changes, limited a priori information is available about which thematic levels could be relevant for different applications. This flexibility allows various uses by planners, by allowing a choice of relevant thematic resolutions or similarity levels, while showing the full vegetation potential at the same time.

Supplementary material

Data S1. – Potential natural vegetation sensu Tüxen: answers to common concerns.
Data S2. – Details of the methodology of the MPV estimation.
Table S1. – Vegetation types.

Supplementary materials are available at www.preslia.cz

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Mnohovrstevná klasifikace krajiny založená na potenciální vegetaci

Klasifikace krajiny založené na kombinaci různých typů vegetace napomáhají pochopení charakteru krajiny a její ekologické obnově. Běžné klasifikace krajiny obsahující jediné tematické rozlišení však mohou krajinnou strukturu příliš zjednodušovat. Cílem této studie bylo vytvořit a otestovat formalizovanou klasifikaci krajiny, založenou na jejím úplném vegetačním potenciálu, tzv. mnohonásobné potenciální vegetaci (MPV). Studovali jsme dvě oblasti: hrubé měřítko představovalo území celého Maďarska, jemné měřítko zemědělská krajina v oblasti Körös-Maros na jihovýchodě země. Hierarchické shlukování a ordinace byly použity k vymezení typů krajin na základě složení typů potenciální vegetace v obou prostorových měřítcích. Po rozdělení výsledného dendrogramu na několika úrovních a vynesení výsledků do map a ordinačních diagramů bylo vybráno nejrelevantnější členění a rozdělení skupin bylo statisticky testováno. Krajinné jednotky založené na vegetaci poměrně dobře odpovídaly biogeografickým poznatkům na obou úrovních tematického rozlišení, pokud studie zahrnovala celou zemi. Vymezení krajinných jednotek a jejich interpretace na základě typických potenciálních habitatů na ně vázaných těžilo z použití série tematických rozlišení. V případě Körös-Maros přístup založený na mnohonásobné potenciální vegetaci zdůraznil nejen přítomnost dobře známé luční vegetace, ale také rozšíření jiných typů krajiny a potenciální výskyt lesních porostů v dnes nezalesněné oblasti. Jemnější tematické rozlišení navíc naznačilo možnost vzniku nového typu krajiny podél dočasných malých toků. Kombinace shlukovacích a ordinačních metod zlepšila interpretaci typů krajin. Použití potenciální vegetace jako vstupních dat umožnuje klasifikovat také v současnosti přeměněné krajiny. Série map dovolují flexibilní volbu tematického rozlišení pro konkrétní účely.

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