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PRIMARY RESEARCH PAPER

The effects of small-scale heterogeneity on biomonitoring of desmid phytobenthos in Central European temperate mountain peatlands

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Abstract Biomonitoring of the ecological status of peatlands is often based on the analysis of the dominant groups of phytobenthos, such as desmids (Desmidiales, Zygnematophyceae, Streptophyta). The most commonly used framework is based on the NCV index, which assesses the conservation value of wetlands based on the ecological traits of the desmid taxa comprising the natural assemblages. However, microphytobenthos is often characterized by remarkable small-scale variability even within ecologically homogeneous sites, and it is not clear how this heterogeneity affects the indicative values of individual samples. In this study, we compared the community structure and the NCV index scores of 32 samples collected on a microscale level in two mountain peatland pools in the Ore Mts. (Czech Republic). The observed variability was compared with regional data from a total of 96 sites. The results showed not only a significant spatial autocorrelation within individual sites, but also a relatively stable community structure and corresponding NCV values in relation to regional variation. This shows that reliable biomonitoring of peatland localities can be based on a relatively small number of samples from each pool, as the NCV index provides a robust framework compared to the small-scale variability within these localities.

Keywords Biomonitoring · Desmids · NCV index · Peatlands · Phytobenthos

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Introduction

Phytobenthos in peat bogs represents a diversified community, typically consisting of lineages and taxa that are restricted to dystrophic wetlands with low pH and limited nutrient availability. In boreal and temperate peat bogs, the microphytobenthos community is usually dominated by representatives of diatoms, Cyanobacteria, and desmids, i.e. representatives of the order Desmidiales from the class Zygnematophyceae (Mataloni, 1999; Neustupa et al., 2013; Küttim et al., 2017; Casa et al., 2024). A number of species from the latter group are exclusively associated with peatland habitats (Coesel & Meesters, 2007). In addition, many desmid taxa are particularly sensitive to fluctuations in the environmental characteristics of their habitats, so their distribution is considered a very good indicator of the ecological stability of peatlands (Coesel, 2001). However, other desmids have broader ecological niche and occur in environments with more diverse abiotic features, including sites

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that have been disturbed by anthropogenic activities or in newly restored peatland habitats (Coesel, 1982; Neustupa et al., 2023). These characteristics of desmids have been used for ecological monitoring, in particular based on the nature conservation value (NCV) index (Coesel, 2001; Stastny, 2010; Neustupa et al., 2023). This index is based on an analysis of the species composition and species richness of desmid assemblages and the regional rarity and ecological sensitivity of individual taxa in three different pH ranges corresponding to the conditions of the main wetland types in temperate and boreal landscapes. This index belongs to the category of biomonitoring frameworks that assess the conservation value of natural ecosystems based on the community structure of a key organism group that reflects the overall ecological status of individual sites (Capmourteres & Anand, 2016). A number of studies and regional surveys have shown that the NCV index is an invaluable tool for assessing the ecological value of individual peatland localities in terms of their importance for nature conservation and restoration schemes (Paul et al., 2017; Hansen et al., 2018; Van Dam & Meesters, 2021).

However, the performance of the NCV index in relation to the heterogeneity of desmid communities occurring at relatively homogeneous sites has been relatively understudied. While the temporal stability of individual taxa or entire desmid assemblages at specific localities has been documented by a number of long-term field surveys and floristic studies (Šimek, 1997; Lenzenweger, 2000; Stastny, 2009; Hansen et al., 2018), there are much less data on their spatial heterogeneity on a microscale. This refers to the variability in the phytobenthic community composition at small scales of a few tens of centimetres or metres, i.e. at the level of individual bog pools or ditches. Researchers conducting floristic surveys of phytobenthic assemblages often report that in some cases it is sufficient to sample one or two metres away in the studied pools, and the epipelon or metaphyton composition can differ significantly (Benedetti-Cecchi, 2001; Coleman, 2002; Machová-Černá & Neustupa, 2009). In addition, some previous studies have shown that desmid assemblages can be spatially autocorrelated even in relatively homogeneous environments with very similar abiotic conditions on a scale of tens of centimetres to metres among samples (Machová-Černá & Neustupa, 2009; Neustupa et al., 2012; Svoboda et al., 2014).

While it is typical for phytobenthic samples to be taken from only one or a few spots within pools during biomonitoring surveys, the published index values often refer to these entire sites (Paul et al., 2017). However, individual pools or their systems within bogs or fens can often be complex in shape, with multiple lobes and areas covered to varying degrees by macrophytes (Vitt, 2006). In addition, pools within bog systems are often interconnected, with widely varying seasonal water levels, so that microphytobenthos cells can be transported among pools. How does this spatial and microhabitat differentiation effect the structure of desmid assemblages and their NCV index values? Is it possible that spatial heterogeneity at small scales is comparable to variability within individual bogs or fens or among nearby peatland systems?

To answer these questions, we selected two localities within peatlands in low altitude mountain ecosystems in the Ore Mts. in the northwest of the Czech Republic for a detailed study. The larger area in this region has recently been investigated with regard to the regional structure of desmid phytobenthos and the associated NCV index values of the individual sites (Neustupa et al., 2023). These habitats in the human-altered landscape of Central Europe have been impacted by various direct human activities, including wetland drainage, peat extraction and pond construction. In addition, in the second half of the twentieth century, these mountainous regions experienced a significant influx of sulphur emissions from thermal power plants in the former Czechoslovakia, which burned sulphur-rich lignite. This led to a remarkable increase in sulphate ion concentrations in the acrotelmic peat layers, which largely replaced the organic anions from dissociated humic and fulvic acids (Hruška et al., 1996) and led to widespread acidification of the waters in these poorly buffered peatland habitats. The effects of these events are still being felt today (Garmo et al., 2014).

However, the sites selected for the present study had the highest NCV index scores, indicating that they were the most valuable out of more than 200 sites surveyed in the region based on the species structure of desmids (Neustupa et al., 2023). They were therefore selected as suitable model localities to investigate the question of whether their relatively high ecological value, as determined from the structure of desmid phytobenthos, is a property of entire pools or whether these extremely complex communities may only be present in relatively isolated patches in the heterogeneous structure of their phytobenthos. In practical terms, this would mean that in the first case, the exceptional natural value of such sites can be detected by analysing a single sample from such a site, and in the second case, it would mean that detailed sampling of phytobenthos from different parts of the site is required. By comparing the species structure of desmids and associated NCV scores from ecologically similar sites in a larger study area, we tested whether variability of these biotic parameters reflects different spatial scales of the samples.

Materials and methods

Study area

The studied peatland sites are situated in the low altitude mountain ecosystems of Ore Mts. (Czech Republic). Peatlands in this region consist of a mosaic of different habitat types ranging from ombrogenous bog pools and minerotrophic spring fens to anthropogenic ponds and pools recently created as a result of ecological restoration schemes (Moorevital, 2018). Both study sites are located in the headwater area of a levelled mountainous plateau at 750 to 850 m a.s.l. and are about 1500 m apart (Fig. 1). The ombrotrophic pool (O), which was selected for detailed sampling, is located in the central part of a relatively pristine peat bog (Fig. 2a), and the nearby minerotrophic spring pool (M) is located in the spruce forest area (Fig. 2b). At the time of sampling, the ombrotrophic pool had a total area of 97 m^2, maximum width of 8 m, length of 32 m and maximum depth of 15 cm. The minerotrophic site had an area of 105 m^2, maximum width of 9 m, length of 30 m and maximum depth of 50 cm (Online Resource 1, Table S1).

Sampling and identification

In July 2024, 16 samples were taken from each locality at 1 to 3 m intervals, so that they essentially covered all parts of each respective site. For each sample, a square of 25 × 25 cm was defined and within this square , the epipelon was thoroughly sampled with a 50-ml plastic syringe from the uppermost 0.5 cm sediment layer so that all available epipelon from this layer was sucked out, which usually meant repeating the process six times. A separate sterilized syringe was used for each sample. The samples were fixed with 96% ethanol + 4% povidone iodine (PVP-I) to a final 8% fixative concentration, which reliably fixed the living cells without any deformation of the desmid cell walls. In addition, metaphytic assemblages were collected by squeezing all available submerged macrophytes and mosses in each square. These samples were fixed in the same way as the samples of epipelon. Comparative regional datasets on desmid species structure and their associated NCV scores of 50 ombrogenous pools and 46 minerotrophic pools and ponds situated in an area of 25 km^2 around both sites studied on a microscale were taken from a recent regional survey (Fig. 1, Neustupa et al., 2023).

Water pH and electrical conductivity were measured with a combined WTW 340i pH/conductivity metre (WTW GmbH, Weilheim, Germany) at the time of sampling in the field. As a rule, the samples were processed immediately after returning from the field. Five microscopic slides (22 × 22 mm) of each sample were examined at ×200 magnification under brightfield illumination using a Leica DM2500 light microscope (Leica Microsystems, Wetzlar, Germany). To identify the smaller taxa, magnification ×400 was used. Class-level abundances of individual species in samples were estimated using a semi-quantitative scale as follows: 1 = less than 5 cells (scarce); 2 = 6–50 cells (rather abundant); and 3 = more than 51 cells (very abundant). Desmids were delimited as all taxa belonging to the monophyletic order Desmidiales. Thus, in the current phylogenetic concept, this includes the families Peniaceae, Gonatozygaceae and Closteriaceae, Desmidiaceae and the genus *Netrium* (Hess et al., 2022).

Data analysis

Multivariate patterns in the community structure of the samples were visualized using 2-D non-metric multidimensional scaling (NMDS), using Euclidean distance to calculate the distance matrix among sites (Clarke, 1993). Species loadings were shown by projecting them as vectors onto the ordination plot showing their correlation with the NMDS coordinates. The reliability of the scaling procedure was estimated by Kruskal's stress value evaluating the goodness of fit between the original distances among sites in the

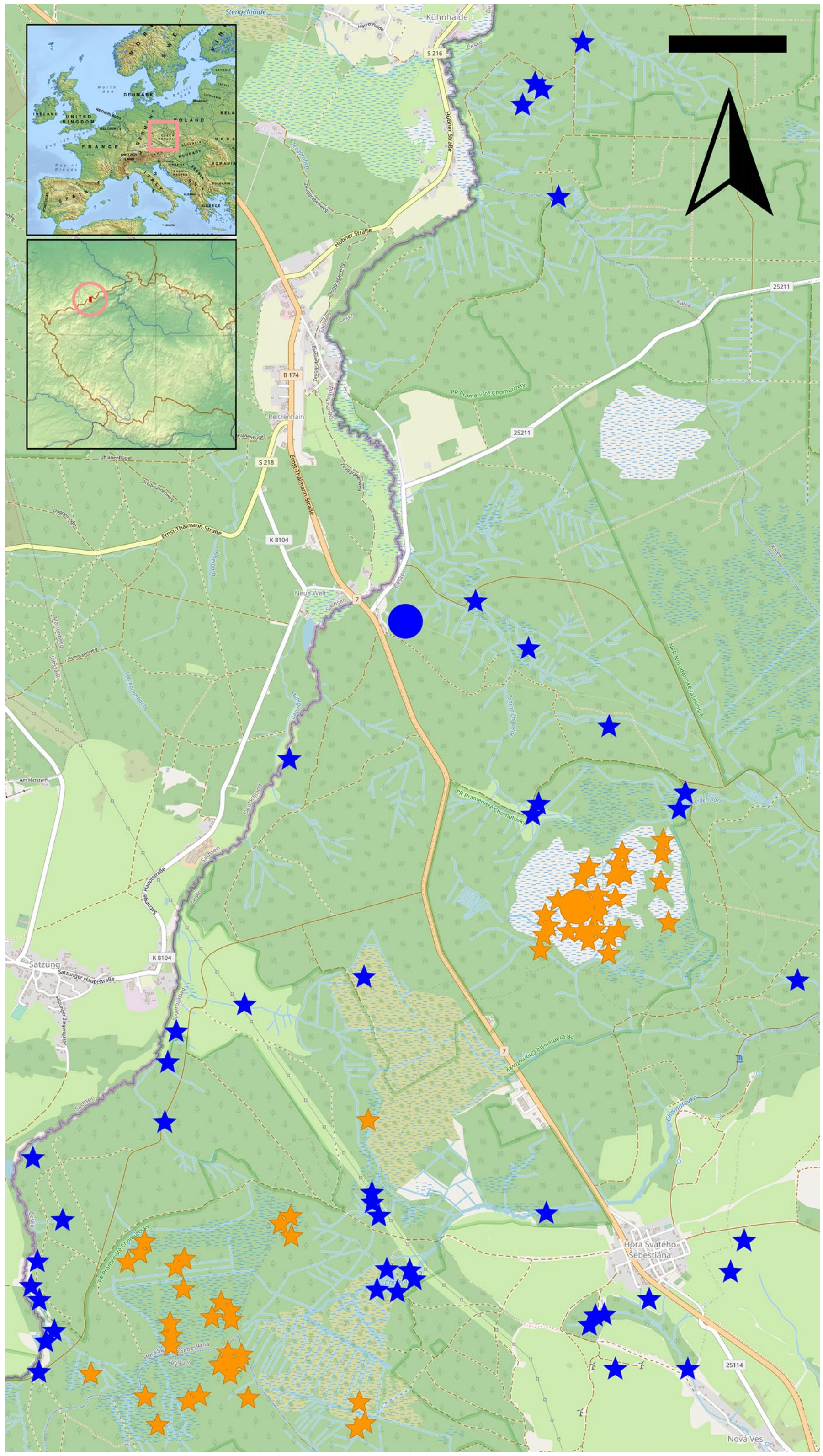

Fig. 1 Location of the study area in the context of Europe and the Czech Republic with the position of the individual samples. Ombrotrophic sites of the regional dataset are marked in orange asterisks, regional minerotrophic sites in blue asterisks. Position of the two sites studied on a microscale is shown by large circles (orange for the ombrotrophic site and blue for the minerotrophic site). Scale bar = 500 m

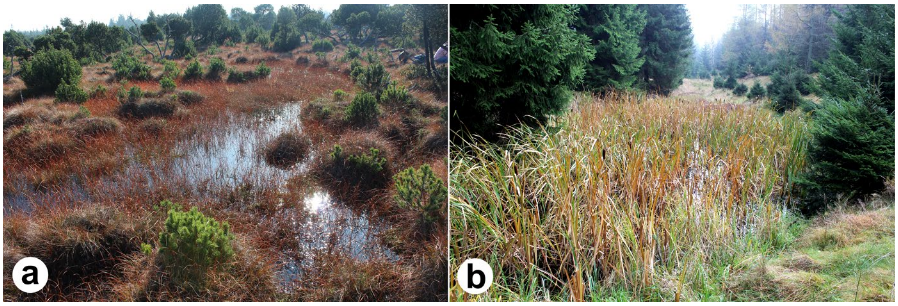

Fig. 2 Photographs of **a** the ombrotrophic site and **b** the minerotrophic site sampled on a microscale

multivariate space and the scaled distances in NMDS ordination space (Clarke, 1993).

Spatial autocorrelation, i.e. the relationship between the spatial distance of individual samples and their species composition, was tested using two parallel techniques. First, the two-matrices Mantel test was used to evaluate the matrix correlation between the Euclidean distances among sites and their spatial distances. Significance of this correlation was tested by permutation test with 9,999 replicates. Second, the congruence between the NMDS ordination and the spatial map of the samples was evaluated by Procrustes superimposition, which minimizes the squared differences between a pair of two-dimensional configurations (Bookstein, 1991; Peres-Neto & Jackson, 2001). The resulting Procrustes sum of squares indicated the goodness of fit between the desmid community structure and spatial distances among samples. The results were visualized by a Procrustes superimposition plot showing the positions of the sites in two superimposed configurations. One advantage of this analysis, therefore, was that the superimposition plot allowed to detect individual sites or groups of sites that were potentially deviating from the prevailing trend in the relationship between their species structure and spatial distance (Peres-Neto & Jackson, 2001). The permutation Procrustes test, which involves randomization of site assignments, was based on 9,999 random replicates.

Evaluation of differences in multivariate dispersions of the samples taken at the microscale from a single pool and those collected at the regional scale was based on bootstrap estimates of average regional dispersion values. For this purpose, 16 samples were randomly taken out of the regional dataset (with replacement). Subsequently, the multivariate dispersion of such a random subset was computed based on the Euclidean distances among samples in the NMDS ordination space. This process was repeated 999 times. Finally, the multivariate dispersion of the dataset from a single pool was compared to the distribution of values based on the random datasets from the regional set. The observed values falling below the 5% percentile of the randomly created distribution were then considered significant.

The desmid-based nature conservation value (NCV) index was calculated based on published indicator values of individual taxa in Central European peatland habitats (Stastny, 2010. The total species richness and the sum of regional rarity and ecological sensitivity values of individual taxa in each sample were determined (Coesel, 2001). The conversion of these taxon-specific scores into the final NCV scores for individual samples was based on the modified tables for three different pH ranges (Coesel & Meesters, 2007; Neustupa et al., 2023). The NCV index then takes values from 0.0 to 10.0, with high scores indicating exceptionally valuable sites based on species richness of the desmid assemblages, and their overall regional rarity and ecological sensitivity traits. A detailed description of the modified NCV index, including conversion tables for each of the partial components, is given in Neustupa et al. (2023). Differences in variance of NCV levels among samples from a single pool and those collected at the regional scale were evaluated by bootstrap estimates of average regional NCV variance values. Also in this test, 16 samples were randomly taken out of the respective regional set of NCV scores and variance of this random subset was computed. This process was repeated 999 times. Then, the variance of NCV scores from a single pool was then compared with the distribution of values based on the regional set.

The NMDS analyses and the Mantel tests were conducted in PAST, ver. 4.10 (Hammer et al., 2001). Computation of NCV scores and bootstrapping tests were performed using utility scripts in R, ver. 4.0.5 (R Core Team, 2024). The analyses of multivariate dispersions were conducted using the function *betadisper* implemented in the *vegan* package, ver. 2.6–2 (Oksanen et al., 2022). Similarly, the Procrustes analyses were done using the functions *procrustes* and *protest*, implemented in *vegan*, ver. 2.6–2. All scripts used for these analyses are available online at https://doi.org/10.5281/zenodo.14210066, together with corresponding input files.

Results

At the two sites examined in detail on a microscale, a total of 53 species of desmids were found in 32 samples (Online Resource 1, Table S1). Of these, a total of 11 species occurred in the ombrotrophic pool. All samples taken from this site were highly acidic and their pH was relatively homogeneous, varying between 3.8 and 4.1, with a median value of 4.0. The minerotrophic site had a higher pH and a total species richness that reached 42 species. The pH values of this site ranged from 5.3 to 5.8, with a median value of 5.6. The conductivity values clearly differentiated between both habitat types, yielding median values 70.5 µS/cm for the samples taken in the ombrotrophic site (standard deviation = 11.3) and 32.0 µS/cm for the minerotrophic site (standard deviation = 4.3) (Online Resource 1, Table S1). A total of 109 species occurred in the entire analysed set, including the regional samples from both habitat types.

The location of samples taken from both analysed pools was consistently marginal with respect to their habitat types across the region in the ordination spaces produced by NMDS (Fig. 3). However, all samples collected at the microscale from both pools were consistently clustered in relatively homogeneous groups close to each other. This significant similarity was confirmed by the analyses of multivariate dispersions, which showed that the values of this parameter were always significantly lower within these sites than in randomly created subsets of the regional datasets (site O: multivariate dispersion = 3.74, $P = 0.005$; site M: multivariate dispersion = 2.95, $P = 0.002$).

The samples from the ombrotrophic pool often contained some taxa with high indicative value for the determination of the NCV index. For example, *Cosmarium sphagnicola* West & G.S. West dominated in all 16 samples from this site, followed by *Staurastrum scabrum* Brébisson (10 of 16 samples) and *Actinotaenium silvae-nigrae* (Rabanus) Kouwets & Coesel (11 samples). A rarer and spatially restricted occurrence was recorded, for example, for *Tetmemorus flensburgii* Van Westen and *Haplotaenium minutum* (Ralfs) Bando, which were only ever found in one sample (Online Resource 1, Table S1). Samples collected on the microscale from the minerotrophic site also repeatedly contained several species with high indicator parameters. These included *Staurastrum forficulatum* P.Lundell and *S. minimum*

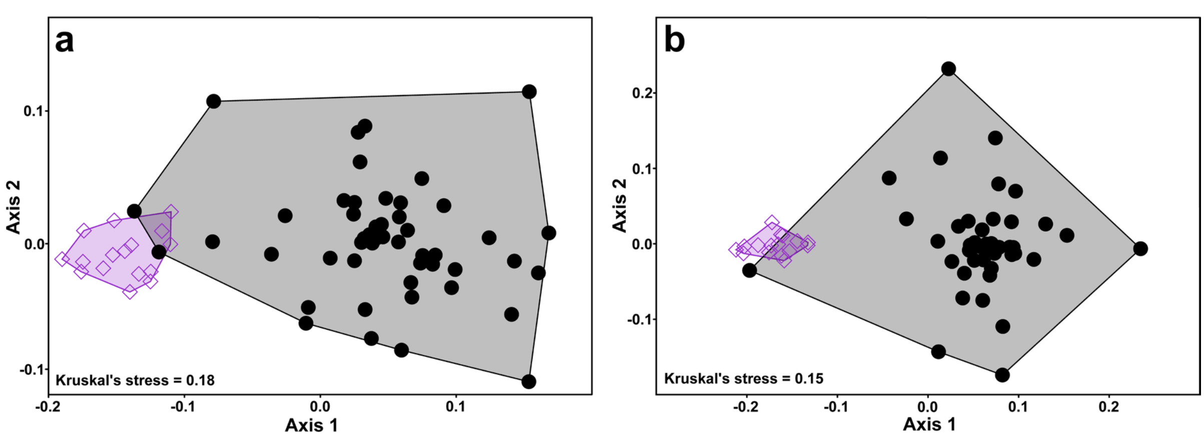

Fig. 3 2-D NMDS ordination plot of species composition in the samples, showing the relative positions of the regional samples (black circles) and those sampled on a microscale within a single site (purple diamonds) in **a** ombrotrophic and **b** minerotrophic peatland localities

Coesel, which were present in all 16 samples taken at this site. In addition, *Closterium calosporum* var. *brasiliense* Børgesen occurred in 12 of the 16 samples, and *Cosmarium paragranatoides* Skuja was found a total of 9 times.

Given the pH levels of the samples, the ombrotrophic locality was classified in the strongly acidic class for the computation of the NCV index. Similarly, all samples from the minerotrophic site belonged to the slightly acidic class. The total NCV index scores for the individual samples at the microscale ranged from 6.0 to 6.6 for the ombrotrophic locality and from 6.4 to 7.8 for the minerotrophic site (Online Resource 1, Table S1). These values were consistently at the upper limit of the overall regional range of NCV scores in the respective habitat types (Fig. 4). The relative stability of these values of the samples from both sites was then supported by bootstrap tests on the variances of the NCV scores. In both cases, the observed variance values within the sites were significantly lower than in the random subsets of the regional datasets (site O: within-site variance = 0.044, $P = 0.001$; site M: within-site variance = 0.127, $P = 0.001$).

The samples in the ombrotrophic site were found to be positively spatially autocorrelated. This phenomenon was shown by both the Mantel tests and the Procrustes analyses (site O: Mantel $r = 0.332$, $P = 0.0045$, Procrustes $r = 0.569$, $P = 0.0039$). This means that the spatially closer samples were significantly more similar in their species composition than the samples further apart. Visually, in the ombrotrophic pool, there was a striking similarity among the samples nos. 1–3, which were located in the left part of the ordination space, yielded by NMDS of the samples taken from this site (Fig. 5a). In contrast, samples nos. 12–16, which were located in the opposite part of the study site, were also all clustered in the opposite part of the ordination area, typified by the presence of *Netrium oblongum* (De Bary) Lütkemüller or *Staurastrum scabrum*. At the same time, however, the position of some samples from the ombrotrophic pool in the ordination space deviated from their actual spatial pattern. Examples of this are samples nos. 6 and 11, which also showed relatively large residual distances to the configurations superimposed by the Procrustes analysis (Fig. 5c, e).

An even stronger spatial autocorrelation was detected at the minerotrophic site (site M: Mantel $r = 0.329$, $P = 0.0034$, Procrustes $r = 0.722$, $P = 0.0003$). This showed that the group of spatially close samples nos. 6–9 located in the left part of the ordination area was typical of the species *Euastrum neogutwinskii* (Schmidle) Homfeld, and *Micrasterias papillifera* Brébisson ex Ralfs (Fig. 5b). In contrast, samples nos. 13–16, taken in the spatially opposite parts of this pool, were differentiated by the occurrence of species such as *Cosmarium humile* Nordstedt ex De Toni, *Staurodesmus triangularis* (Lagerheim) Teiling or *Staurastrum tetracerum* Ralfs ex Ralfs (Fig. 5d, f).

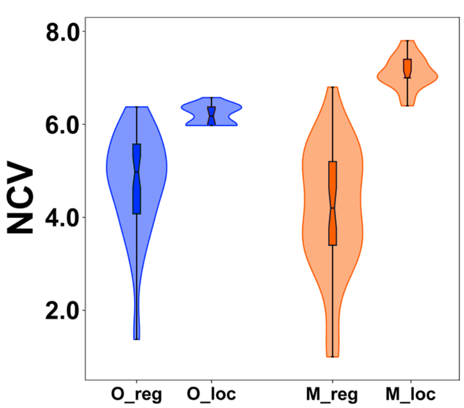

Fig. 4 Variation in the NCV scores among regional and local samples in ombrotrophic (O) and minerotrophic (M) peatland localities

Discussion

Our results consistently showed that the unique species structure of the desmids at the two water bodies sampled in detail, compared to the regional datasets, was evident in virtually every single sample taken at those sites. This was clearly shown, for example, by the relatively homogeneous positions of the samples from each of these sites compared to the regional samples within individual habitat types as shown by the combined ordination analyses. Similarly, these properties of all samples from both sites are reflected in their relatively high NCVs, which were generally always near or at the upper end of the values achieved regionally (Fig. 4). Thus, this is also a fairly clear answer to the basic question of this study. One or two samples from any location within these sites would be sufficient for a baseline determination

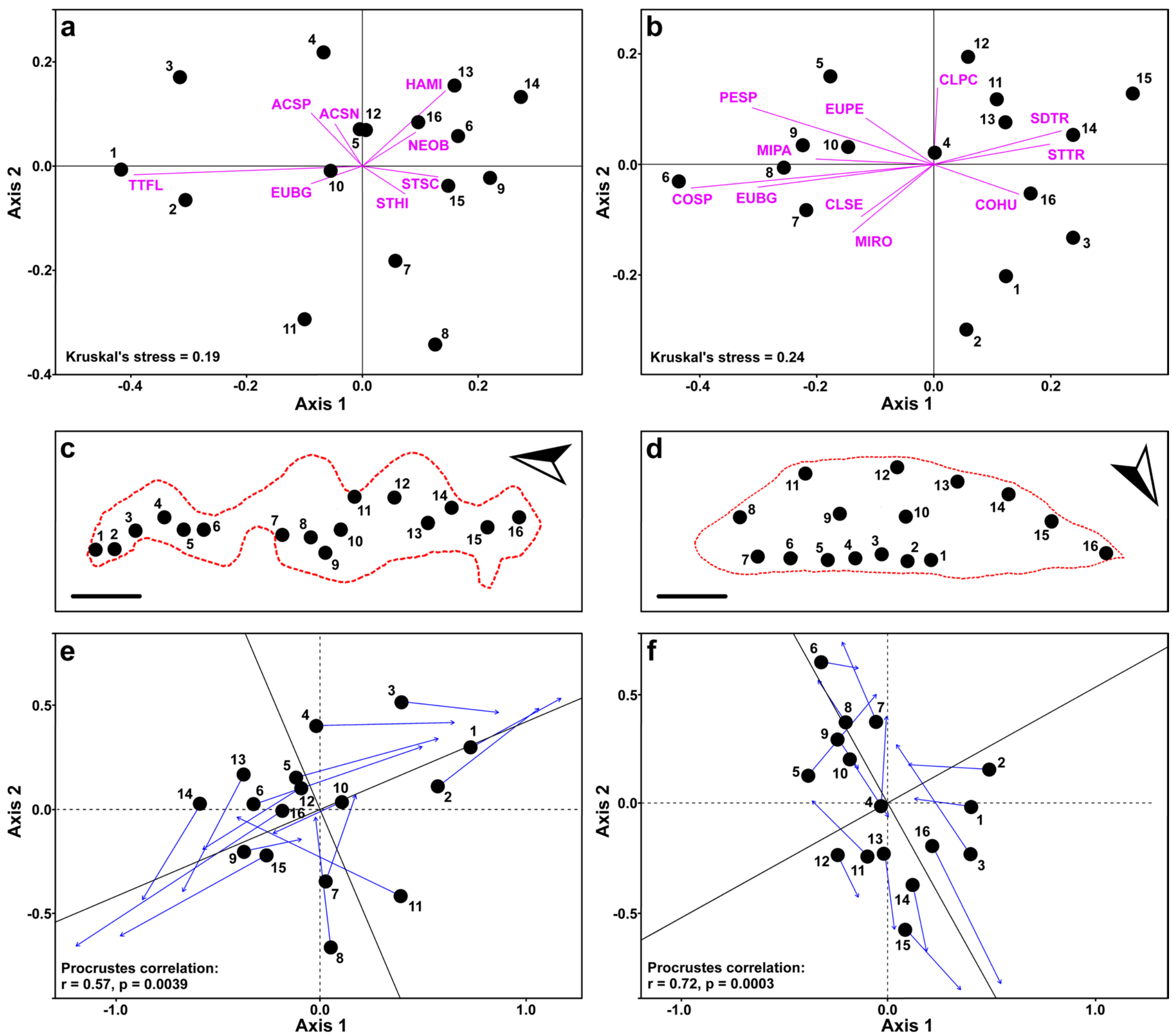

Fig. 5 Positions of samples taken on a microscale in the two-dimensional NMDS ordination plots showing the projections of the key desmid taxa onto the ordination spaces for **a** the ombrotrophic and **b** the minerotrophic sites. Actual spatial arrangement of samples at **c** the ombrotrophic and **d** the minerotrophic localities. The Procrustean plots showing the superimposition of spatial structure on the NMDS ordination plots at the **e** ombrotrophic and **f** minerotrophic sites. Designations of the taxa are explained in Table S1. Scale bar = 5 m

of their exceptional value in terms of desmid-based biomonitoring.

Nevertheless, it was also found that samples collected on a microscale in both study sites were spatially positively correlated. This means that closer samples were more likely to be similar to each other than samples taken from more distant parts of the pools. Thus, it cannot be said that the observed variability among the samples of phytobenthos collected on a microscale within each site was solely a random fluctuation in the composition of their desmid assemblages. Indeed, some species clearly showed small-scale distribution only in a limited part of the studied sites. Therefore, if only one point is sampled, these taxa may not be recorded at a particular locality.

Significant spatial autocorrelation on the scale of decimetres or metres within environmentally homogeneous sites has been previously observed in desmids (Neustupa et al., 2012) as well as in other groups of phytobenthos (Rindi & Cinelli, 2000; Černá, 2010; Kahlert & Rašić, 2015). It has been argued that such variability can be caused by several factors, such as priority effects in habitat colonization (Svoboda et al., 2014), varying dispersal rates among taxa (Kahlert & Rašić, 2015) or small-scale heterogeneity in the environment, i.e. water level fluctuations (Neustupa et al., 2024) and variation in abiotic factors due to artificial barriers that reduce water runoff (Černá, 2010). However, it should also be noted that the observed variability among samples collected on the microscale is also likely related to the accidental detection of rare species that are present at the site but are only detected with some probability in individual samples. Thus, the resulting variability in species composition was probably an interplay of these various factors.

Nevertheless, these various possible causal factors are often correlated with each other, their effects overlap, and it is not easy to decide what causes the observed variability. Our study did not attempt to explain the possible causal causes of small-scale variability, but it should be mentioned that in ecologically marginal habitats, such as peatlands at lower altitudes of temperate mountain ranges, individual sites are affected with increasing frequency by severe environmental stress due to partial or total desiccation caused by meteorological extremes during the summer season (Hájková et al., 2011; Neustupa et al., 2024). This stress can further be exacerbated in areas affected by past industrial emissions due to the oxidation of the reduced sulphur compounds stored in the surface peat sediments, which are facilitated in the dried parts of pools (Van Dam & Meesters, 2023). At such locations, the small-scale variation can be amplified by both increased environmental instability and local extinction of taxa. In addition, it was repeatedly shown that freshwater microphytobenthos is typical for an inherent within-site variation of individual samples taken from different parts of a locality (Cattaneo, 1990; Vymazal & Richardson, 1995). This has been attributed to genuine random processes in within-site species distribution, as well as to possible differences in microhabitat traits, and to varying environment (King et al., 2006). Therefore, the standard sampling approach adopted in numerous phytobenthos monitoring studies has been to collect several subsamples from defined site and to pool these in order to make a single composite sample (Vymazal & Richardson, 1995; King et al., 2006).

However, it is interesting to see from our results that the desmid-based NCV scores of the samples were not significantly affected by such variability. The evaluation of its individual components, such as species richness or the summed scores for regional rarity and ecological sensitivity, by abundance classes makes this index relatively robust and resistant to small-scale variation such as those observed in this study. This demonstrates the reliability and usefulness of this biomonitoring framework for broader studies focusing on regional patterns of peatland phytobenthos and the identification of sites of particular conservation concern. This robustness of the NCV index with respect to small-scale variability of desmid assemblages is a significant advantage when processing large numbers of samples, as it allows sampling to be based on one or just a few samples for each study site, such as a single peat bog or fen pool. For example, sampling an area of approximately 1 m^2 to obtain just one mixed sample would safely yield a representative NCV index score, while providing a fast and efficient sampling pattern within the regional biomonitoring surveys. It should be noted that this is broadly consistent with related studies that have focused on the performance of diatom-based biomonitoring indices used to assess the ecological status of various freshwater habitats (Kelly, 2002). These studies have shown that the index values are relatively robust with respect to spatial variation of diatoms on a microscale within sites, regardless of whether they are streams and rivers (Lavoie et al., 2005; Kahlert & Rašić, 2015) or lakes (King et al., 2006).

In addition to site-specific biomonitoring, however, the distribution of species richness in peatland habitats at the regional scale is also of crucial importance for nature conservation purposes. Here, regional variation was shown to significantly amplify locally observed values, even when detailed sampling covered sites with relatively high species richness. It turned out that the two sites that were sampled in detail did not contain the majority of the regional diversity of their respective habitat type. The local values accounted for 41.6% and 68.8% of the species present in the regional survey for the minerotrophic and ombrotrophic sites, respectively. It should be noted that the higher proportions in the ombrotrophic dataset are most likely related to the overall lower species richness and variability of desmid assemblages at these sites, i.e. their relatively lower beta-diversity

(Coesel, 1982; Nováková, 2007; Gonzáles Garraza et al., 2019). Therefore, when assessing the results of this study in terms of their potential implications for nature conservation strategies, it is important to consider that the sites that stand out due to their exceptionally high indication values, while containing rare and ecologically sensitive species, cannot necessarily be considered fully representative microcosms in terms of overall diversity. Thus, in this case, protection of a larger number of sites within the region should be recommended in order to conserve the diversity of phytobenthos in the peatland landscape.

Conclusions

Summing up, our study has shown that biomonitoring of peatland phytobenthos using a desmid-based NCV index is relatively robust with respect to small-scale variation in the structure of desmid assemblages within individual homogeneous sites. Although the assemblages are spatially autocorrelated on the scale of units of metres, this variation is limited compared to regional beta-diversity, both in ombrotrophic bog pools and in minerotrophic fens and ponds. For biomonitoring studies employing the NCV index, this means that the value of individual sites can probably be determined on the basis of one or more samples taken at each site within more comprehensive surveys.

From a climatic point of view, most peatlands in the temperate zone represent marginal habitats that are distributed close to their natural limits (Vitt, 2006; Čížková et al., 2013). The current climate instability poses an increased risk of environmental disturbances that may push these ecosystems beyond the limits of their ecological stability. In Central European peatlands, the dynamics of these changes include an increased frequency of summer desiccation, which can lead to a significant decline in the ecological value of these wetlands (Neustupa et al., 2024). Monitoring and mitigation of these processes through conservation management can be a key tool for protecting the biodiversity of organisms associated with these habitats. The identification of particularly valuable sites through biomonitoring of phytobenthos is therefore a prerequisite for the effective conservation of peatland ecosystems. We believe that our study has shown that the desmid-based NCV index is a suitable, reliable and robust tool for this need.

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Data availability Primary data used for the analyses are available as Online Resource 1.

Code availability The R scripts used for the analyses are available online at: https://doi.org/10.5281/zenodo.14210066.

Declarations

Conflict of interest The authors declare no conflict of interest.

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