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Research article

Peatland restoration in Norway – evaluation of ongoing monitoring and identification of plant indicators of restoration success

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Norway launched a national action plan on wetland restoration in 2016. So far, 90% of the restoration effort has been on peatland restoration, with about 140 mires restored so far. There are three main restoration goals stated in the action plan: 1) limit greenhouse gas (GHG) emission, 2) climate adaptation and 3) improved ecological condition. Quantifying the outcome of the restoration actions is necessary to evaluate whether the goals of the action plan are met. A vegetation monitoring protocol was suggested before restoration started and has been implemented at five restoration sites. As the peatland restoration effort in Norway is increasing, it is timely to evaluate if the data currently collected can measure peatland restoration outcome. We evaluate the monitoring protocol based on statistical analyses of the data collected at two sites, describe how indicator species can be identified using generalized composition data used as the basis for classifying habitats in Norway (EcoSyst framework), and suggest the way forward for peatland restoration monitoring in Norway. Data collected according to the monitoring protocol can document changes in species composition at restoration sites, but has limitations when the ecological complexity at the sites increases and reference sites are unavailable. We argue that adjusting the monitoring protocol will: 1) facilitate alignment with existing peatland research; 2) connect better with monitoring programs where data is collected applying EcoSyst framework principles; and 3) enable upscaling to cover the wide variation emerging in peatland restoration.

Keywords: bog, boreal, ecological restoration, mire, Nordic, ombrotrophic

Introduction

Peatland restoration plays an important role in safeguarding existing soil carbon stocks (Günther et al. 2020), and will also be an important contribution to reach the

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Kunming-Montreal Global Biodiversity Framework Target 2 on restoration of degraded land to enhance biodiversity and ecosystem functions and services (CBD Secretariat 2022). Successful restoration is necessary to meet global targets of limiting climate change and halt biodiversity loss. The lack of monitoring of actions taken in peatland restoration may result in uncertainty and unpredictive restoration outcomes (Andersen et al. 2017, Chimner et al. 2017, Rochefort and Andersen 2017, Brudvig and Catano 2022), but can document restoration success when it is conducted (González and Rochefort 2019, Nugent et al. 2018). In order to make evidence-based decisions (Cooke et al. 2018, Reed et al. 2022) and guide restoration of functional peatlands (Rochefort and Andersen 2017), it is necessary to identify suitable indicators for monitoring (Reed et al. 2022), and also standardize methods for measure restoration outcome (Evju et al. 2020a).

As elsewhere, water-saturated areas in Norway were traditionally considered wasteland, and about 7000 km^2 of mires have been drained for agricultural and forestry purposes (Joosten et al. 2015). As a European late bloomer, a national action plan on wetland restoration was adopted in 2016 (Norwegian Environment Agency 2016), focusing on restoration of drained and afforested peatlands in protected areas. The restoration strategy in Norway has three main goals: 1) limit greenhouse gas emission, 2) climate adaptation and 3) improve ecological conditions.

To ascertain whether restoration measures improve ecological condition, a reference state is needed for comparison. Nybø and Evju (2017) defined a reference condition and good ecological condition for terrestrial ecosystems in Norway, including wetlands. The reference condition is defined as intact nature, and for peatlands this is characterized by intact dynamics with natural disturbance and succession processes. Intact hydrology is considered the most important aspect of this. Consequently, indicators based on vegetation should reflect changes in hydrology. Intact hydrology allows for peat accumulation, and peatlands in good ecological condition support vegetation that contribute to peat formation. Therefore, vegetation-based indicators of ecological condition in peatlands should also relate to potential peat formation.

Norway has a wide range of mire types due to a varied topography and climate, which is unique on an international scale (Joosten et al. 2017). This substantial regional variation (Moen 1999) is also reflected in the distribution of mire species, with six phytogeographical groups commonly recognized (Flatberg et al. 1994, Flatberg 2013). Consequently, the diagnostic value of a species is not necessarily uniform throughout Norway. Classification and categorization are necessary to deal with this complexity, and in Norwegian nature management the EcoSyst framework (Halvorsen et al. 2020) is used. In the EcoSyst framework ('Nature in Norway' – NiN) peatlands are classified according to their vegetation and hydromorphology. The latter is used in the attribute system, yielding the mire massif types (e.g. plateau raised bog). The former is the basis of the type system, and uses turnover of species along ecological gradients to separate major (e.g. open fen versus bog) and minor wetland ecosystem types (e.g. poor carpet versus extremely rich carpet). The three principal ecological gradients in mire vegetation are (ombrotrophic) – poor – rich, carpet – hummock, and mire margin – mire expanse (Sjörs 1948), and in the EcoSyst framework these are examples of local environmental complex-variables (LECs). Generalized composition data (GSD) is used to differentiate minor types along the LECs based on the species turnover. The GSD datasets contain the species that regularly occur in the species pool of a community in a region and are based on expert judgement (Halvorsen et al. 2020). Importantly, these datasets are compiled with national level representativity in mind, encompassing all vegetation regions and including species of various phytogeographical groups. This makes the GSD datasets prime sources for identification of peatland restoration species indicators.

A peatland restoration monitoring protocol including vegetation parameters was suggested before restoration commenced (Hagen et al. 2015) and so far implemented at five mire sites (Kyrkjeeide et al. 2021). By the end of 2022, 140 peatland sites have been restored. Ideally, as peatland restoration effort increases, the uncertainty in restoration outcome ought to decrease (Brudvig and Catano 2022). Evaluating the success is of major importance to guide future work and apply additional actions where needed. As the restoration effort in Norway is increasing, upscaling of monitoring is also needed. Furthermore, the restoration goal of improving ecological condition is vague, and a link to vegetation- or species-based indicators should be defined and adopted. We will evaluate the strengths and shortcomings of the implemented monitoring protocol based on statistical analyses of the data collected at two sites. Next, we describe how indicator species can be identified using GSD datasets in the EcoSyst framework. Lastly, we suggest the way forward for peatland restoration monitoring in Norway.

Material and methods

Study sites

Kaldvassmyra is situated in central Norway (63°43′27″N, 11°35′22″E), and was protected as a nature reserve in 1984. It is dominated by plateau raised bog mire massifs, but also includes spring-fed extremely rich fens, and the calcareous lake Kaldvatnet (Moen 1969, Moen and Moen 1977, Moen et al. 1983). The mire is situated at 185 m a.s.l. in the southern boreal vegetation zone and weakly oceanic vegetation section (Moen 1999), i.e. with a relatively mild and moderately wet climate conducive to mire formation and peat growth. Limestone dominates the area, and calcareous gyttja forms a layer between the mineral substrate and the overlying peat. Kaldvassmyra is considered one of the best developed raised bogs of Norway and was restored in 2016 as one of the first localities in the wetland restoration program of Norway. The restored ditch is placed in a soak between two plateau raised bog massifs and was blocked (plugged) by using timber and peat extracted close to the ditch (Fig. 1).

Figure 1. The site Kaldvassmyra before restoration (left) had a forested ditch crossing the bog interior and after restoration (right) the trees have been removed and the ditch has been plugged. Vegetation data have been collected along transects K1–K5, indicated as white lines. Photo: ©norgeibilder.no, 5 July 2009 (left), 2 June 2017 (right).

Left-over timber, twigs and branches was used to fill in the ditch between the peat dams.

Hildremsvatnet is a large (29 km^2) nature reserve in central Norway, where the valley Nyvassdalen (63°51′16″N, 10°1′59″E) in the northern part of the protected area hosts several ditched and restored mires in a ca. 2 km^2 area 75–125 m a.s.l. The dominant mire massif types are sloping fen, flat fen and floodwater mire, mostly with poor and intermediate vegetation. Nyvassdalen is situated in the southern boreal and middle boreal vegetation zone and the clearly oceanic vegetation section (Moen 1999), i.e. with a wet and relatively mild climate. Granite and gneiss dominate the bedrock, which is often covered by a thin stratum of moraine. The site has been heavily ditched, with no areas left undisturbed. Hydrological restoration was carried out in 2019 by plugging ditches using peat excavated at the site (Fig. 2).

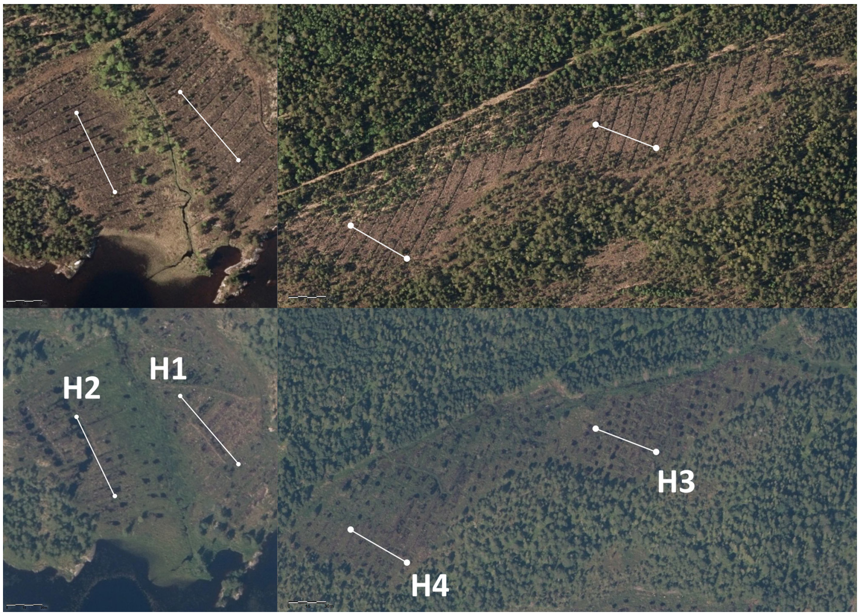

Figure 2. The site Hildremsvatnet before restoration (above) had ditches across the mires at regular intervals with pine trees growing at the site and after restoration (below) the site has been extensively restored leaving several small ponds from extraction of peat for peat dams. Vegetation data have been collected along transects H1–H4, indicated as white lines. Photo: ©norgeibilder.no, 9 June 2012 (above), 8 September 2022 (below).

Vegetation monitoring and data collection

Vegetation was monitored at Kaldvassmyra in 2015, 2018 and 2021, before, two, and five years after restoration, respectively. The reference transect was only monitored in 2021. Vegetation was monitored at Hildremsvatnet in 2018 and 2021, before and after restoration. Data was collected according to a vegetation monitoring protocol established prior to the first monitoring (Hagen et al. 2015).

Transects at Kaldvassmyra were 50–80 m long, with the midpoint placed in the ditch and the far ends reaching intact parts of the peatland (Fig. 1). Close to the ditch the vegetation is minerotrophic, whereas the far ends are ombrotrophic. The transects were standardized to 50 m at Hildremsvatnet as the site had multiple, parallel ditches (Fig. 2). Four transects were established before restoration at both sites, and a fifth transect (reference, Fig. 1) was established at Kaldvassmyra in 2021. At Hildremsvatnet, all mires had been ditched and no reference area was available for establishing a reference transect.

Species data was recorded in 2.5 m segments (hereafter called species lines) spaced by 10 m intervals laterally along the transects, with the first species line starting at meter 0 (Fig. 3). We used a point intercept method to record data every 10 cm: A rod was held vertical to the ground and all species touching the rod were recorded. A species was only recorded once at each point, even if it touched the rod at several places. Species names follows the Species Nomenclature Database of the Norwegian Biodiversity Information Center.

Statistical analyses

To assess the impact of hydrological restoration on species composition over time and with distance from the ditch, a non-metric multidimensional scaling (NMDS) was used to visualise and calculate scores for every species line per transect based on species presence over time and distance from ditch. The NMDS ordinations were run with Jaccard dissimilarity measures since the data contain presence/absence and are therefore binary. We compiled the species recorded in the species lines along transects for three and two monitoring years at Kaldvassmyra and Hildremsvatnet, respectively. The iterative NMDS algorithm was repeated 32 times with a different starting configuration each time, to avoid convergence on a suboptimal solution. Two-, three- and four-dimensional NMDS were performed. The NMDS stress values for the species composition-based distance matrix were 0.187, 0.047 and 0.041, respectively. The two-dimensional solution was chosen as the two plot axes might correspond to the factors: 'year' and 'meter from ditch'.

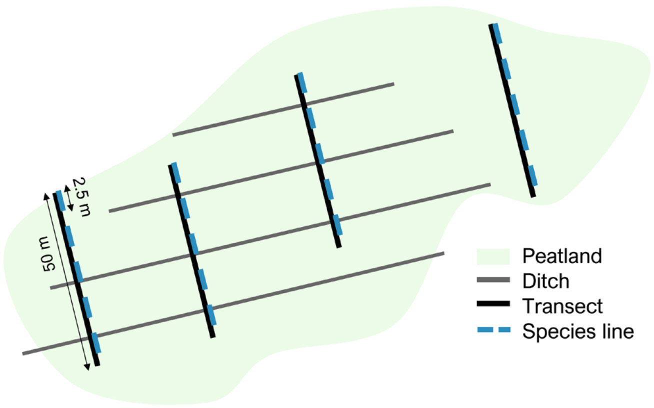

Figure 3. The monitoring protocol used to evaluate restoration success of peatland restoration in Norway collects vegetation data along transects crossing old ditches. Species data are collected using an intercept point method recording species every 10 cm in shorter segments (species lines) along the transect.

For Kaldvassmyra, NMDS point scores from the transects were further used in a polynomial regression model, the NMDS point scores are explained by distance from the ditch, distance from the ditch$^{1/2}$ and year. A good model should only be as complex as necessary to describe a dataset, so we started with the most complex model. We compared regression models using anova until the most parsimonious model was found. Difference in species composition along transects were considered statistically significant at $p < 0.01$.

All data handling and analyses were performed in R statistical software (ver. 4.2.2; www.r-project.org). 'Tidyverse', 'labdsv' and 'readxl' packages were used for data cleaning, 'vegan' was used for NMDS modelling and 'ggplot2' was used to create figures (Roberts 2019, Oksanen et al. 2022, Wickham 2016, Wickham et al. 2019, Wickham and Bryan 2022).

Identifying indicator species

We use the generalized composition data (GSD) of the EcoSyst framework as a basis for identifying ecologically relevant indicator species for peatland restoration. Among the three principal gradients in mire vegetation (Sjörs 1948), the carpet – hummock gradient is most closely linked to hydrology. Following successful restoration, a directional change in species assembly should be expected, and this would materialize as a relatively lower prevalence and cover of hummock species, and a relatively higher prevalence of lawn and carpet species. This is quantified by Halvorsen et al. (2016) in the carpet-hummock GSD, which shows the distribution of species along this gradient, and it provides a baseline for assessing changes in hydrology.

In the EcoSyst framework, the carpet – hummock gradient corresponds to the LEC duration of period without inundation (TV), which has the five categories carpet – lower lawn – upper lawn – lower hummock – upper hummock (Halvorsen 2015, Halvorsen et al. 2020). In the carpet – hummock GSD the species are assembled in altogether 14 realised species groups reflecting their occurrence and abundance among these categories (Halvorsen et al. 2016). Both the position and the width of the distribution along the gradient are relevant in this context. Species with a wide distribution are poor indicators of hydrological change, whereas species with a narrow distribution are good indicators. Thus, we used the 14 species groups to score a species indicator value. If a species spans all

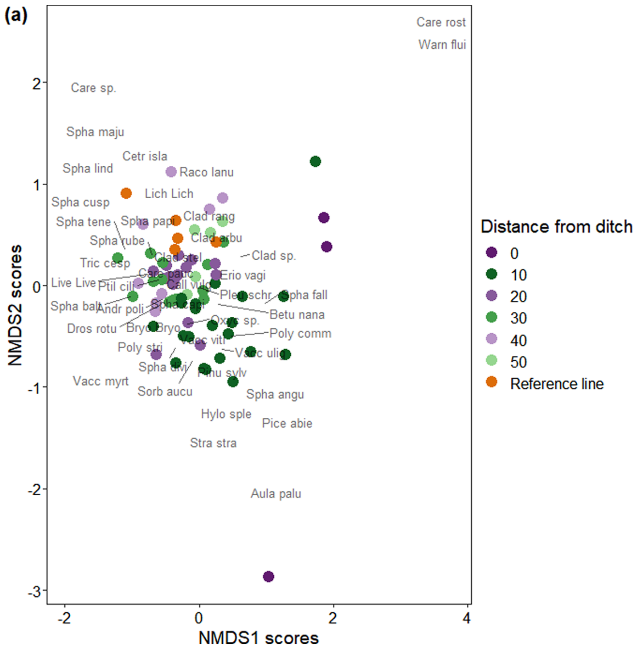

Figure 4. Non-metric multidimensional scaling (NMDS) ordination plot showing species and 73 species lines (communities) at Kaldvassmyra with species line distance from ditch (a) and species line vegetation sampling years (b). All values were calculated with Jaccard dissimilarity matrix.

five categories along TV, it is assigned the score 0, meaning it has no value as an indicator. Further, occurrence in four categories is assigned score 1, three categories score 2, two categories score 3 and, lastly, species only found in one category have a score of 4, which is the highest indicator value.

We used the datasets from Kaldvassmyra and Hildremsvatnet to evaluate the suitability of the species data recorded under the current monitoring protocol and identified the species with high indicator value (score 3 and 4).

Results

The results from Kaldvassmyra show that the species composition changes with distance from the ditch (Fig. 4–5). The NMDS analysis conducted explained at least 90% of the variation observed in the data, with a stress value of 0.18. The species lines placed furthest from the ditch, typically at 40–50 m distance, group together with the species lines along the reference transect. In contrast, species lines placed in or near the ditch (0–10 m distance) are further from the reference species lines both at the NMDS1 and NMDS2 axes in the plot (Fig. 4). Figure 5 shows how species composition along NMDS1 axis changes in relation to the distance from the ditch (NMDS1 ~ meters from ditch + meters from ditch, $r^2 = 0.59$, $p < 0.001$, with stress values 0.19), and that the species composition for most of the species lines placed 20–50 m away from the ditch is similar to the species composition of the reference species lines.

Along the first NMDS axis (Fig. 4), more nutrient demanding species are found with higher NMDS scores than nutrient poor species. The species lines to the right are placed in or close to the restored ditch and the nutrient demanding species were

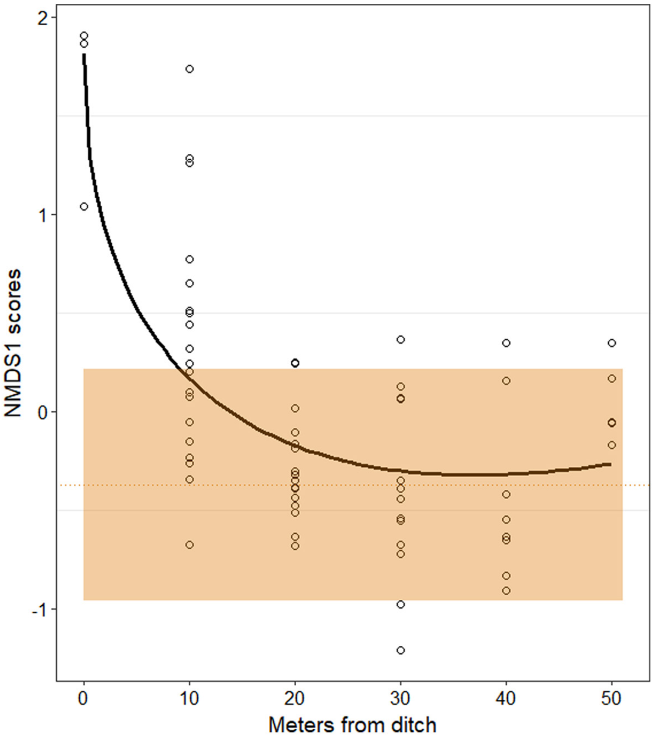

Figure 5. Relationship between NMDS scores from the first axis of species communities from species lines along transect K1–K4 at Kaldvassmyra and meters from the ditch. The orange dotted horizontal line represents the mean values for species lines along the reference transect (K5) with ±1 SD indicated by light orange shading.

only recorded after restoration, indicating a nutrient release following restoration. Along the second NMDS axis (Fig. 4), most of the species distribute along the mire expanse–mire margin gradient, with typical mire expanse species having high NMDS2 scores, including species such as *Sphagnum cuspidatum*, *S. majus* and *Racomitrium lanuginosum,* which all are common on oceanic bogs (Fig. 4). The reference lines and many species lines distant from the ditch group among these species. However, one of the reference lines are distant from the others, likely because it completely lacks hummock species and thus represents a typical hollow vegetation community. No other species lines have this species composition, indicating that hummock vegetation dominates.

At Hildremsvatnet, the overall species composition seems to be unchanged before and after restoration as the species lines are randomly distributed across the NMDS plot (Fig. 6). The NMDS analysis conducted explained at least 75% of the variation observed in the data, with a stress value of 0.23. However, along transect H4 the species lines have increased NMDS scores at both axes after restoration, indicating that there are fewer species associated with mire margins and forests (distributed mainly with low scores along the NMDS axes, Fig. 6).

Indicator species based on the carpet – hummock GSD

We identified ten species in the Kaldvassmyra dataset and six species in the Hildremsvatnet dataset with indicator value 4, and 16 and ten species, respectively, with indicator value 3 (Table 1). Among species with indicator value 4, seven species, mostly dwarf shrubs, are restricted to upper hummock vegetation. Together with three *Sphagnum* species that are restricted to carpet vegetation, the species with high diagnostic value represent each extreme along the carpet – hummock ecological gradient. The group with indicator value 3 also has mostly hummock species, with the moss *Warnstorfia fluitans* being the only carpet species. In total, eight of the species with value 3 are bryophytes and three are lichens (Table 1). Many of the species have few occurrences in the dataset, and at Hildremsvatnet the number of occurrences along the species lines are evidently lower after restoration (Table 1).

Discussion

Evaluation of the vegetation monitoring

Our results from Kaldvassmyra show that the species composition of the species lines at the far ends of the transects resemble the reference, and that the initial design of the monitoring protocol indeed captures trends in species composition and structures moving from the ditch and into more intact parts of the peatland. However, this approach was not applicable at Hildremsvatnet as the mires were thoroughly ditched and no parts of them were left intact.

The species lines yield data on species composition and can indirectly quantify plant frequency (Halbritter et al.

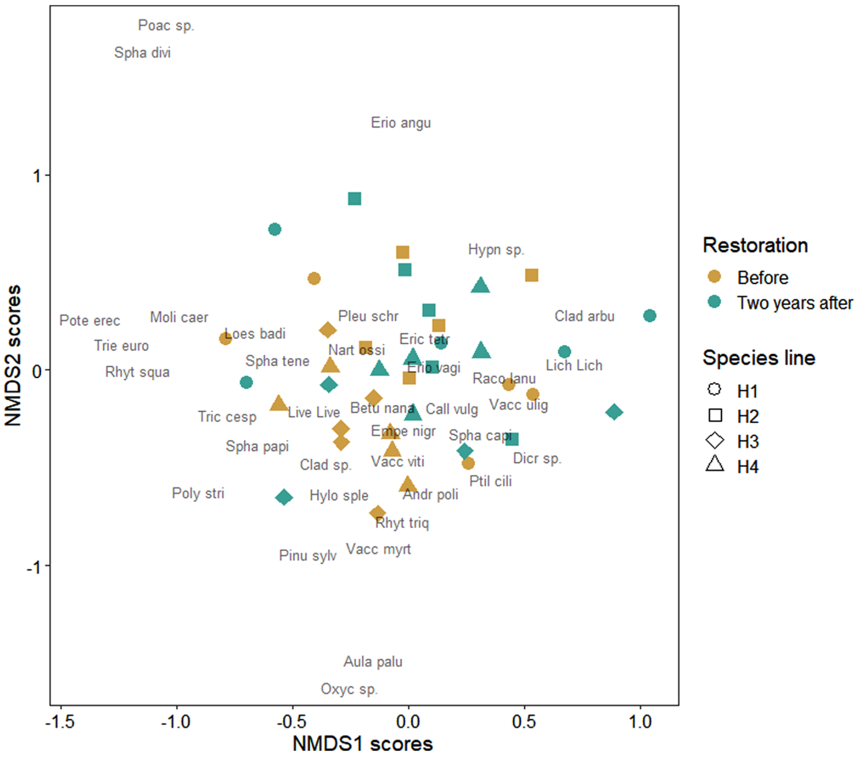

Figure 6. Non-metric multidimensional scaling (NMDS) ordination plot showing species and 39 species lines (communities) at Hildremsvatnet across four transects (H1–H4, coloured points) and two sampling years (different shapes). All values were calculated with Jaccard dissimilarity matrix.

Table 1. Species at Kaldvassmyra and Hildremsvatnet identified to have an indicator value of three or four based on the generalized composition dataset used to delimit habitat types in Norway and their respective placement along the carpet – hummock gradient. For each species, the table shows functional group, indicator value, affinity along the carpet – hummock gradient, and the number of occurrences along the species lines at each census for each site.

Species	Functional group	Indicator value	Affinity	Kaldvassmyra (before, two years after, five years after)	Hildremsvatnet (before, two years after)
Sphagnum cuspidatum	Sphagnum	4	carpet	yes (4, 1, 0)	no
Sphagnum lindbergii	Sphagnum	4	carpet	yes (0, 12, 5)	no
Sphagnum majus	Sphagnum	4	carpet	yes (14, 0, 0)	no
Empetrum nigrum	dwarf shrub	4	upper hummock	yes (60, 92, 72)	yes (22, 0)
Hylocomium splendens	moss	4	upper hummock	yes (25, 29, 36)	yes (25, 9)
Picea abies	shrub/tree	4	upper hummock	yes (4, 0, 1)	no
Sphagnum capillifolium	Sphagnum	4	upper hummock	yes (75, 88, 46)	yes (3, 8)
Vaccinium myrtillus	dwarf shrub	4	upper hummock	yes (0, 1, 0)	yes (6, 0)
Vaccinium uliginosum	dwarf shrub	4	upper hummock	yes (9, 16, 19)	yes (5, 2)
Vaccinium vitis-idaea	dwarf shrub	4	upper hummock	yes (6, 8, 4)	yes (1, 1)
Warnstorfia fluitans	moss	3	carpet – lower lawn	yes (0, 0, 8)	no
Sphagnum papillosum	Sphagnum	3	lower lawn – upper lawn	yes (14, 24, 3)	yes (5, 1)
Sphagnum tenellum	Sphagnum	3	lower lawn – upper lawn	yes (31, 33, 18)	yes (13, 10)
Loeskypnum badium	moss	3	lower lawn – lower hummock	no	yes (1, 0)
Carex pauciflora	Graminoid	3	upper lawn – lower hummock	yes (0, 0, 1)	no
Trichophorum cespitosum	Graminoid	3	upper lawn – lower hummock	yes (37, 32, 28)	yes (44, 13)
Calluna vulgaris	dwarf shrub	3	lower hummock – upper hummock	yes (112, 132, 101)	yes (41, 81)
Cladonia arbuscula	lichen	3	lower hummock – upper hummock	yes (95, 59, 69)	yes (18, 16)
Cladonia rangiferina	lichen	3	lower hummock – upper hummock	yes (9, 53, 21)	no
Cladonia stellaris	lichen	3	lower hummock – upper hummock	yes (1, 1, 0)n	no
Pinus sylvestris	shrub/tree	3	lower hummock – upper hummocky	yes (3, 5, 2)	yes (11, 3)
Pleurozium schreberi	moss	3	lower hummock – upper hummock	yes (133, 154, 111)	yes (117, 29)
Ptilidium ciliare	liverwort	3	lower hummock – upper hummock	yes (34, 81, 35)	yes (7, 0)
Racomitrium lanuginosum	moss	3	lower hummock – upper hummock	yes (28, 45, 53)	yes (193, 90)
Rubus chamaemorus	herb	3	lower hummock – upper hummocky	yes (14, 33, 9)	no
Sorbus aucuparia	shrub/tree	3	lower hummock – upper hummock	yes (0, 0, 1)	no
Sphagnum fuscum	Sphagnum	3	lower hummock – upper hummock	yes (29, 73, 72)	no

2020). Results from Kaldvassmyra show differences in species composition with distance from the restored ditch. Thus, the method can be used to evaluate change and direction of change over time. However, five years after hydrological restoration at Kaldvassmyra, there were no statistical indications of restoration induced changes in species composition. This is comparable to other studies (Punttila et al. 2016, Howie et al. 2009). When visiting the site after restoration, the water level along the blocked ditch was constantly at the surface level in the interior of the mire complex. At the far ends of the ditch, it is placed in mire margin or in a former lagg between mire margin and forest, and here the water level fluctuates substantially. In dry periods the restored ditch in the mire margin has even been seen to dry out completely. This indicates either that the hydrology has only been partly successfully restored, or that the underlying water table fluctuation in mire margin is much higher than the fluctuation in mire expanse. Our results show that the transects in mire margin vegetation are dominated by hummock and mire margin species, and this reflects the variability of the water table. Based on our data, it is not possible to separate the effects of an innate water table variability from a variability introduced by ineffective hydrological restoration. That would require a comparison with intact mire margin vegetation.

While the species lines clearly yield useful information, this approach does not provide species abundance and percentage cover data. The latter can be estimated from point intercept data, but overestimates the cover compared to relevés (Rochefort et al. 2013). Collecting cover data is particularly relevant for sites with more extensive restoration such as Hildremsvatnet, especially to be able to evaluate vegetation recovery on bare peat. At this site, the species composition was not changed, and analysing the species composition alone could not reveal that most of the bottom layer was removed during restoration (Kyrkjeeide et al. 2021). The relevé method has the advantage of collecting cover data and is the most commonplace method of gathering vegetation data in restoration projects (Evju et al. 2020a). Indeed, cover and abundance are two of four domains recently identified as important to measure in peatland research and monitoring to create datasets for synthesising evidence needed to inform decision makers (Reed et al. 2022). Abundance data can be used to calculate mean trait values for plots such as ecological indicator values (Ellenberg et al. 1991, Tyler et al. 2021) to compare ecological function before and after restoration, hence it is a useful tool to assess restoration success. Furthermore, the point intercept method captures mainly common species and is thus less suitable for monitoring biodiversity (Godínez-Alvarez et al. 2009). Monitoring rare species might increase the number of indicator species in the dataset.

Relevés are an integral part of the Norwegian monitoring program of terrestrial ecosystems (ANO, Tingstad et al. 2019). Modified ANO monitoring protocols have been developed to monitor the effect of removal of alien conifer in protected areas (Kolstad et al. 2020), and the ecological condition of the threatened habitat type calcareous grassland (Evju et al. 2020b), where the number of relevés established depend on the habitat size. Relevés have been used for decades in mire ecology (Moen 1990), and the vegetation data used in the GSD datasets of the EcoSyst framework is also collected using the relevé method (Halvorsen et al. 2016). International peatland restoration monitoring schemes also use the method (MoorLIFE 2013, González et al. 2014, Pilkington et al. 2016). Comparing the species line method and the relevé method, the latter has the advantage of providing cover data (Rochefort et al. 2013), and it is easier to align with historical vegetation datasets and current, large-scale monitoring programmes. This would be an advantage for sites like Hildremsvatnet, where a reference is lacking. Thus, relevés should be included in monitoring of the outcome in peatland restoration also in Norway.

Indicator species based on the carpet – hummock GSD in the EcoSyst framework

Using the GSD datasets to identify indicators seems to be a useful approach to evaluate the hydrological condition at restored sites. Among the indicator species with the highest diagnostic value, only strict carpet and strict upper hummock species were represented. Unsurprisingly, hummock species (seven species) dominate, as the datasets cover the situation before restoration and a few years after restoration. The water level drawdown caused by the ditch would favour species thriving in drier conditions. Even though species turnover following restoration may take time (Joosten 1995, Price et al. 2016), certain species can indicate the effect of restoration within years (González and Rochefort 2014). The other group, carpet species (three), were all *Sphagnum* sp., confirming their suitability as candidate indicators in peatland monitoring. However, to make field identification of *Sphagnum* species easier, it should be evaluated whether similar species have the same diagnostic value. A critical evaluation of *Sphagnum* indicators is needed before they are applied.

The carpet – hummock GSD is a generalized representation of the occurrence and abundance of mire species along the carpet – hummock vegetational gradient and is representative for Norway. It uses expert judgement to synthesize vegetation data from several sources (Halvorsen et al. 2016, 2020), including categorization into species groups representing taxa with a similar response to water level regime. The assigned niche widths seem to fit well with field measurements (Gignac 1992). The niche width of the species groups along the carpet – hummock GSD is the basis for our suggested approach with a 0–4 indicator value scale. The validity of the assignment to a given species group is as good as the expert judgement, which again rests on the availability and quality of vegetation data. While expert judgements have weaknesses (Burgman et al. 2011), they are also necessary to make ecological assessments where data is scarce or not well-suited to statistical analyses. In the case of the LEC duration of period without inundation (TV), the five categories (from carpet to upper hummock) are separated based on ordination methods (Halvorsen 2015). We consider these categories well substantiated, and in line with e.g. Sjörs (1948) and Moen (1990). The 13 species groups are assembled according to the diagnostic value of the species, i.e. how well suited the species are for identifying the five categories along TV.

The carpet – hummock GSD includes data on both occurrence and abundance, and the delimitation of the 13 species groups also relies on both parameters. Our 0–4 indicator value scale is intrinsically based on both parameters as well, but considers occurrence data alone when used on a dataset. Further work should be done aiming at establishing an index for restoration outcome based on both the occurrence and abundance of species. The 'Indicator value method' of Dufrêne and Legendre (1997) is an option to pursue as it utilises the abundance and relative occurrence of species across a dataset to identify indicator species (González et al. 2013).

The mire expanse – mire margin GSD should also be applied in evaluation of restoration outcome. Prior to analysis we opted not to include it, because this gradient is more complicated to interpret. However, water level drawdown can create ecological conditions favouring mire margin species, and a shift towards mire expanse species after restoration implies improved ecological conditions, as shown at Kaldvassmyra.

By using the GSDs, we establish a direct link to the EcoSyst framework, and this has several advantages. Mapping of nature types under the auspices of the state sector in Norway should be based on the EcoSyst framework (Meld. St. 14 2015–2016), and this is now done routinely, generating large amounts of data. By coupling the restoration indicator value of species to existing mapping or monitoring, an overview of changes in ecological condition is feasible within the scope of current programmes.

A disadvantage of the national monitoring (ANO) is the lack of species data on bryophytes. Bryophytes often dominate peatlands and are key indicators of peatland function and structure (Vitt and House 2021). Thus, we argue that bryophytes should be included in monitoring of peatlands, even though they are well-known as difficult to identify. In fact, seven of the highly diagnostic indicator species we identified in the carpet – hummock GSD are *Sphagnum* species. *Sphagnum rubellum* has been shown to be an early indicator of success in restored horticultural peat extraction sites where active revegetation was applied (González et al. 2014). Norwegian peatland restoration does not yet include active revegetation, but sites like Hildremsvatnet with high frequency of bare peat could benefit from this, and reestablishment of *Sphagnum* spp. would indicate success.

Optimizing peatland restoration monitoring

Mire restoration in Norway is currently evaluated based on a limited number of sites, and the geographical, regional and hydromorphological representation is skewed. In addition, sites with high drainage impact have required more radical restoration actions than low impact sites, which complicates interpretations of monitoring data. We suggest adjusting the monitoring protocol to gain better knowledge about restoration quality.

The Kaldvassmyra case suggests that the species lines (point intercept method) in the current monitoring protocol yields useful information on the effect of peatland restoration on vegetation. Thus, we suggest maintaining the species lines approach at the five sites being monitored to ensure compatibility with existing data, but also suggest adding relevés to improve upscaling possibilities. A monitoring set up based on the national monitoring program ANO (modified approach cf. Evju et al. 2020b, Kolstad et al. 2020), will facilitate alignment with existing monitoring programs both nationally and internationally, and provide ground truthing for remote sensing.

The carpet – hummock GSD dataset in the EcoSyst framework has provided the basis for our 0–4 indicator value scale. Species with a narrow niche along this gradient are regarded good indicators of hydrological change, and these turn out to be strictly hummock and strictly carpet species in the Kaldvassmyra dataset. This approach provides a link to the EcoSyst framework, which is the classification system shaping current monitoring and mapping programmes in Norway. Further work is needed to improve the indicator scale by including abundance, and also by including other gradients, notably the mire margin – mire expanse gradient.

We recommend that monitoring of peatland restoration in Norway should:

- Build a reference library and identify indicator thresholds across mire types in Norway. This will ameliorate the problem of missing reference sites.
- Collect species data using relevés and include percentage cover of each species.
- Monitor a larger variation of Norwegian peatlands and any new restoration actions applied, e.g. active revegetation, to evaluate the effect on a broader scale.

This will provide the knowledge base needed to guide future restoration work and improve the ecological condition at already restored sites.

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Data availability statement

Data are available from the Dryad Digital Repository: https://doi.org/10.5061/dryad.hqbzkh1pm (Kyrkjeeide et al. 2023).

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