

Cutting *Juncus*: Management of dense rush to encourage *Sphagnum* establishment on an ex-milled peatland

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SUMMARY

The reintroduction of *Sphagnum* moss is central to the process of peatland restoration in the UK. Dominant *Juncus effusus* is a common problem resulting from eutrophication of peatland, reducing the value of the habitat. In this article we report on the management of an area of dense *J. effusus* to permit the reintroduction of *Sphagnum* onto a milled peat extraction site during restoration towards lowland raised bog. Trial plots were established in a waterlogged area of shallow mineralised peat covered with tall, dense *J. effusus*. Various treatments of repeated brush-cutting together with the removal (or not) of *Juncus* litter were applied, the plots planted with commercially produced *Sphagnum* plugs (BedaHumok® West Pennines 5-species Mix), and followed up over three years. The results indicate that a plausible approach to reduce *J. effusus* where it is dominant and promote *Sphagnum* growth is to cut and windrow *Juncus* twice prior to *Sphagnum* planting, then regularly cut the *Juncus* to facilitate establishment of a *Sphagnum* lawn within the *Juncus* stubble. Cutting less frequently than yearly had little effect on *Juncus* dominance. The chosen *Sphagnum* plugs appeared suitable for this application as most of the five species were evident and thriving at the end of the trial.

KEY WORDS: bog, eutrophic, fen, reintroduction, restoration

INTRODUCTION

Juncus effusus (*Juncus*) is a common, clump-forming, very tall (up to 150 cm) plant of damp grasslands (Fitter *et al.* 1992). Ellenberg values for *Juncus effusus* (Hill *et al.* 1999) indicate a plant that thrives in situations of open light, and damp, generally acidic, lightly fertile conditions (L = 7, F = 7, R = 4, N = 4), and is typical on thin layers of peat where its roots can access an underlying mineral substrate (Richards & Clapham 1941). *Juncus* has a very high rate of seed production (Lazenby 1955), a long period of seed dormancy and potential germination (Moore & Burr 1948), and the plant spreads rhizomally to create a continuous, dense cover (Ashby *et al.* 2020). These characteristics allow *Juncus* to be highly competitive and dominate bare peatlands (McCorry & Renou 2003). While *Juncus* may contribute to bog formation over long timescales, there is now an urgent need to accelerate bog restoration to prevent further loss of carbon stocks and habitat (Nugent *et al.* 2019, Loisel & Gallego-Sala 2022).

Dense *Juncus* shades out other plants (Ervin & Wetzel 2002) and, if growing in a northern peatland

environment, prevents development of the diversity of bog flora which thrives in a more open sward, particularly *Sphagnum* mosses. In degraded lowland bogs, establishment and development of *Sphagnum* is key to repairing the main ecohydrological conditions essential for bog development (Quinty & Rochefort 2003). Additionally, *Juncus*, as an aerenchymatous plant (Blossfeld *et al.* 2011), is a potential conduit for methane from the substrate to the atmosphere (Henneberg *et al.* 2015), so its presence in a peatland under restoration or agricultural conversion measures is antagonistic to the purpose of reducing greenhouse gas emissions.

Cutting the shoots to the base of the plant almost eliminates methane transport from the roots (Henneberg *et al.* 2012). Such aggressive cutting, particularly in late summer, when nutrient supply in the roots has been depleted to facilitate growth and before nutrients can accumulate again through photosynthesis, also significantly reduces regrowth (McCorry & Renou 2003, Kaczmarek-Derda *et al.* 2014). However, regular mowing/cutting of *Juncus* is necessary (McCorry & Renou 2003) to reduce its vitality in the longer term and maintain a sufficiently open sward for *Sphagnum* establishment (Gaudig *et*

al. 2017). This is particularly important in scenarios where conversion of grassland to *Sphagnum*-dominated bog, as a nature-based climate solution (Strack *et al.* 2022), leaves a *Juncus* seed bank or there are remaining local diaspore sources (Gaudig *et al.* 2018). If the nutrient load is reduced, for example by topsoil removal, and nutrient input is low (e.g., Rosinski *et al.* 2021, Kennedy *et al.* 2023), *Juncus* cutting can be an irregular, less onerous operation, leaving some standing material which is useful for supporting *Sphagnum* establishment and growth.

Where sites are also important for breeding birds, *Juncus* can become invasive if not properly managed, reducing the value of the habitat (Coyle *et al.* 2018, Kelly *et al.* 2021). In this scenario, retaining a partial *Juncus* sward may be advantageous to some bird species and the cutting regime may need some adjustment (Nielsen *et al.* 2014, Coyle *et al.* 2018), as long as disturbance during the breeding season is avoided. Shellswell & Humpidge (2018) noted a large increase in wetland birds using a site after several years of *Juncus* management to reduce dominance.

Little Woollen Moss (LWM) is a 105-ha fragment of the once-extensive Chat Moss in the northwest of England (Osborne *et al.* 2024), purchased by Lancashire Wildlife Trust (LWT) in 2012. It has large areas of dense *Juncus effusus* which have limited habitat value. This trial was developed based on the results of smaller trials (Keightley *et al.* 2020) of *Sphagnum fimbriatum* introduction to areas of dense *Juncus* which had been treated with regimes of cutting, cutting and windrowing, trampling, and leaving intact. The earlier trials showed that cutting, with both leaving cut material in place and windrowing, showed the best outcomes for establishment and development of at least one species of *Sphagnum*, and these two treatments were used in the trial reported here. The objective was to establish *Sphagnum* species within the treated *Juncus* area with the expectation that the *Sphagnum* would bind nutrients (van Breemen 1995) and weaken the dominant *Juncus* sward, permitting the introduction of more diverse fen or bog flora. The research questions were:

1. Is repeated *Juncus* cutting necessary after *Sphagnum* introduction?
2. Does *Sphagnum* establish naturally within a dense *Juncus* sward?
3. Does cutting the *Juncus* improve the growth of *Sphagnum*?
4. Does removal of cut *Juncus* stems influence *Sphagnum* growth?

METHODS

Field site

Little Woollen Moss is situated on the edge of Chat Moss, close to areas of high population (Figure 1). Rewetting through bunding and ditch-blocking on Phase 1 (approximately 55 ha of the site) was undertaken soon after site acquisition in 2012 to promote eventual restoration to lowland bog. Phase 2 (~45 ha) was still under peat-extraction tender in 2012. The remaining layer of peat was very thin at 0.5 m on average. Prior to purchase by LWT, a 150 m wide strip of the site running north-south along the western border of Phase 1 was turned over with the underlying sand and clay (a traditional practice to 'improve' the peat; Aikin 1795), with the intention of converting the land to agricultural use (Figure 2). These mineral rich areas were of lower elevation than much of the site and subject to flooding after rewetting (Figure 3) leading to rapid proliferation of dense *Juncus effusus* (*Juncus*) tussocks, which were visible on satellite imagery (Planet Labs 2017) covering approximately 13 % of the Phase 1 area, preventing the establishment of *Sphagnum* and *Eriophorum* species.

Experimental design

Seven adjoining plots of 10 × 10 m were established in an area of continuous dense *Juncus* on LWM (Figure 2). The local topography was defined using LIDAR imagery (Environment Agency 2020) which showed a slope from northeast to southwest, along with depressions and old, infilled ditches where existing or previously-introduced *Sphagnum* was found. Water table depths were recorded monthly at an adjacent dipwell (Figure 3). Treatments were as follows (Figure 4):

- Cut and left (C&L): *Juncus* brush-cut as close as possible to the bases of the plants and cut material left in place (three plots).
- Cut and windrowed (C&W): *Juncus* brush-cut as close as possible (given flooding in places) to the bases of the plants and cut material raked aside to form ridges along the plot edges (three plots).
- Untreated Control (UTC): *Juncus* sward left standing (one plot).

Juncus was brush-cut in late summer (August) 2021 and again just prior to *Sphagnum* planting (termed '1st cuts' or 1C&L, 1C&W): (for example images, see Figure 5). Micropropagated *Sphagnum* plugs (Beadahumok®) were purchased to introduce a range of *Sphagnum* species suited to the conditions and with a specific number per treatment to better-

standardise results. The *Sphagnum* material used was West Pennines 5-species Mix (colloquially known as ‘Pool Mix’), which consists of *S. cuspidatum* (~30 %), *S. denticulatum* (~25 %), *S. fallax*, *S. fimbriatum* and *S. palustre* (~15 % each), which may proliferate in conditions of higher nutrients (except, perhaps, *S. cuspidatum*) and moisture than other *Sphagnum* species. Plugs (200 per planted plot) were planted on 23 Oct 2021 at two together per m² or as near as possible, depending on flooding, in two out of each three *Juncus*-treatment plots (termed PP plots), with the remaining treatment plot deliberately unplanted (UP plot). Plugs were placed between cut *Juncus* stalks for support and to prevent drifting/sinking, and were not placed in open water with no support.

The plots were first surveyed on 07 and 08 Aug 2022 on days of very similar weather, after a long

period of low rainfall. The existing 10 × 10 m plots were marked out in 2 m wide strips running east–west (examples in Figure 5). Starting at the edge of each plot, monitors surveyed the area immediately in front of them, 1 m deep and 2 m wide. *Juncus* cover was estimated on a 1–4 scale (1 = 0–25 %, 2 = 25–50 %, 3 = 50–75 %, 4 = 75–100 %). *Juncus* height (from ground level to the height of the majority of the *Juncus* sward, not the tallest point) was measured first, before the area was disturbed, then the water depth, size of each *Sphagnum* patch (length, width and % ground cover within an imagined oval of those measurements) (examples in Figure 6), and any other vegetation noted (presence only). Thus, 50 areas of 1 × 2 m (termed sub-plots) were fully surveyed within the entirety of each plot, and *Juncus* and *Sphagnum* measurement results could be aligned. The UTC plot was surveyed in the same way. Any

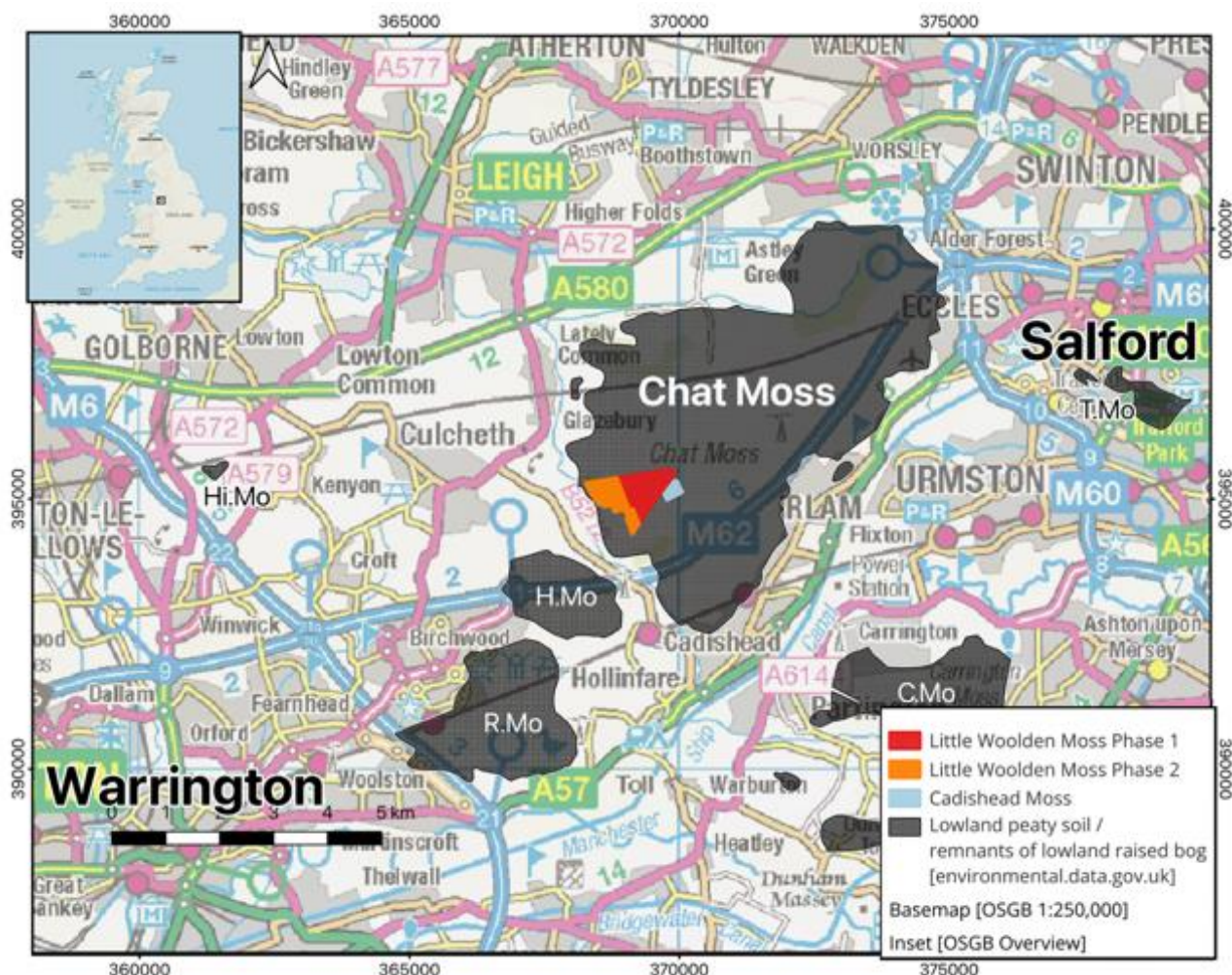


Figure 1. Map of the Chat Moss area in northwest England (UK). The footprint of remaining deep peat (> 0.4 m) within the degraded Chat Moss complex and surrounding peatlands is marked (black), including Carrington moss (C.Mo), Holcroft Moss (H.Mo), Highfield Moss (Hi.Mo), Risley Moss (R.Mo) and Trafford Moss (T.Mo). Cadishead Moss and Little Woollen Moss Nature Reserves are also marked.

Sphagnum deemed to have been washed in from surrounding areas was discounted from the trial results, but was noted and measured for future reporting.

Subsequently, all *Juncus*-cut treatments had a second cutting on the easternmost half of each plot on 19 Sep 2022 (termed 2nd cut or 2C&L, 2C&W for cut treatments, and 2U.C&L, 2U.C&W for the uncut treatments). The cut material was left where it dropped in C&L treatments and raked to the sides on

C&W plots, always taking care not to damage *Sphagnum* clumps and other mosses. Final monitoring of the plots, using the same methods as above, was undertaken on 09 and 10 Nov 2024. There was above-average rainfall in 2024 (01 Jan to 30 Sep LTA 1991–2020 Woodford [Greater Manchester] Met Station = 603 mm; this year, local met station = 658 mm), and the plots were flooded in places (examples in Figure 5). A further site visit was made on 17 Nov 2024 to measure peat depth, pH, electrical

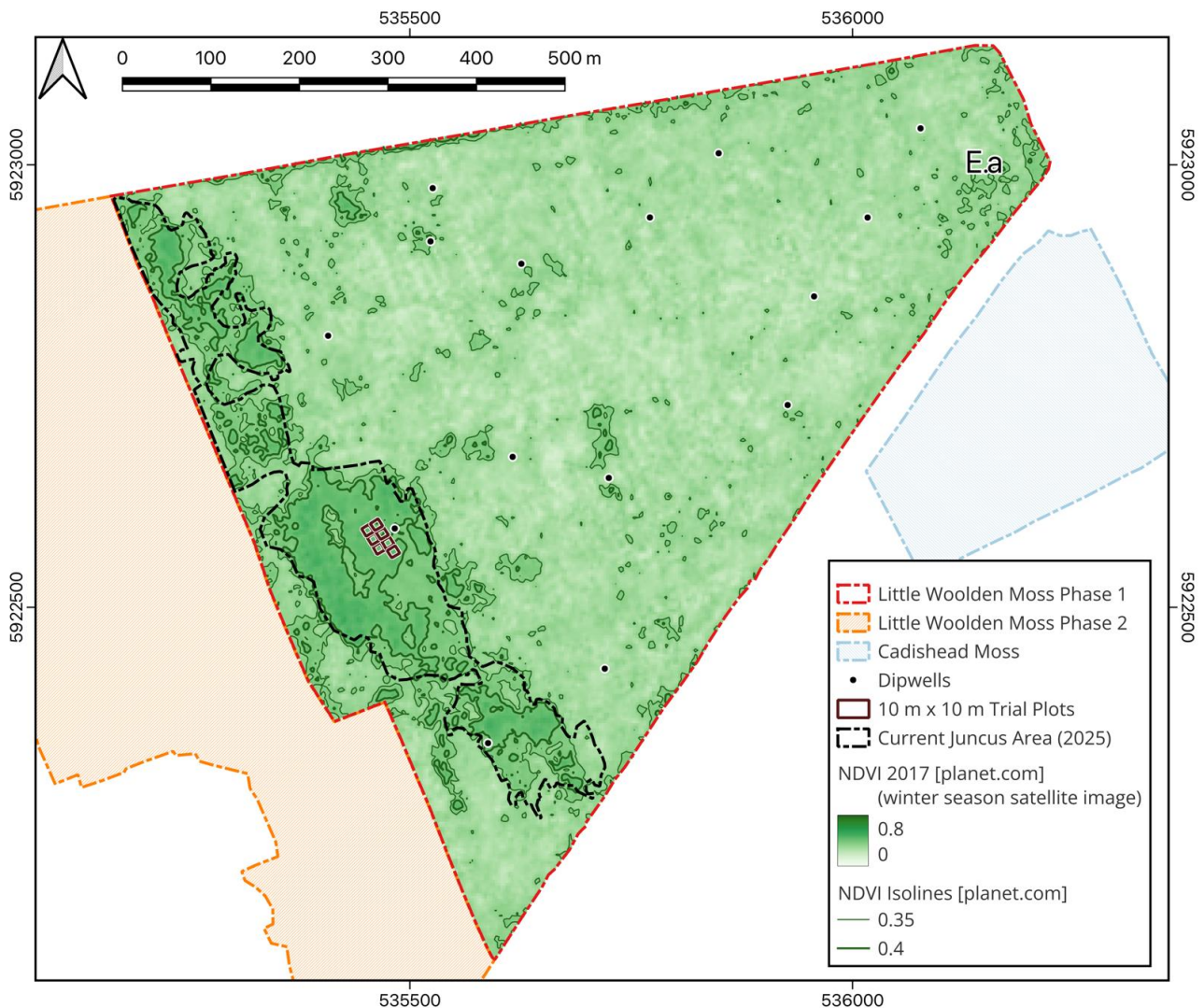


Figure 2. Site plan generated in QGIS. Phase 1 (under restoration since 2012) is outlined in red. The area of mixed clay and peat is situated on the western edge of Phase 1. The 2017 Normalised Difference Vegetation Index (NDVI) base layer (greens) highlights chlorophyll in living plant tissue, mostly dense *Juncus effusus* which established rapidly during an early phase of the peatland restoration in wet areas with exposed mineral soil. At this stage most of the site was bare peat and there was virtually no cottongrass (*Eriophorum angustifolium*) except where it had been introduced at the eastern extreme of the site (E.a). The NDVI is derived from a satellite image acquired during the winter season, hence deciduous *Betula* sp. scrub and *Molinia caerulea* are not highlighted. The current extent of the *Juncus*-dominated area (7.1 ha; outlined in black) is co-located with the 2017 footprint and has not expanded onto adjacent areas of undisturbed peat. The trial plots are marked (brown).

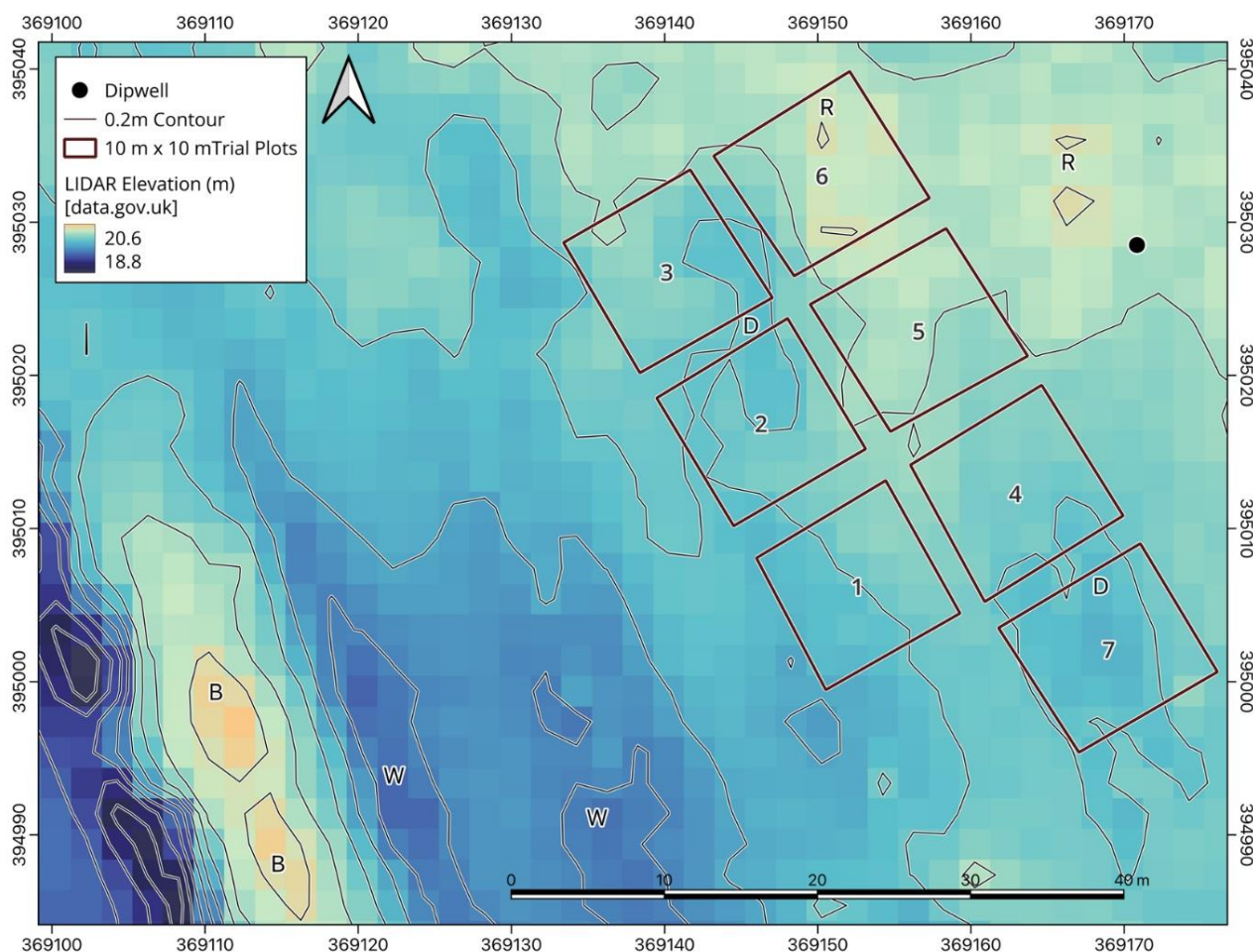


Figure 3. Plan of the trial plots (1 to 7) with local topography marked on the LIDAR base layer. The trial site slopes from northeast to southwest (fall approximately 40 cm in this direction) with deep permanent water (W) to the west of the trial plots retained by a tall peat bund (dam) (B–B). There are small variations in topography across the trial plots resulting from the previous peat extraction, which has left a residual pattern of (mostly filled) north–south ditch lines (D) and intervening ridges (R) resulting in relatively dry and also semi-permanently inundated sub-sections of the trial plots.

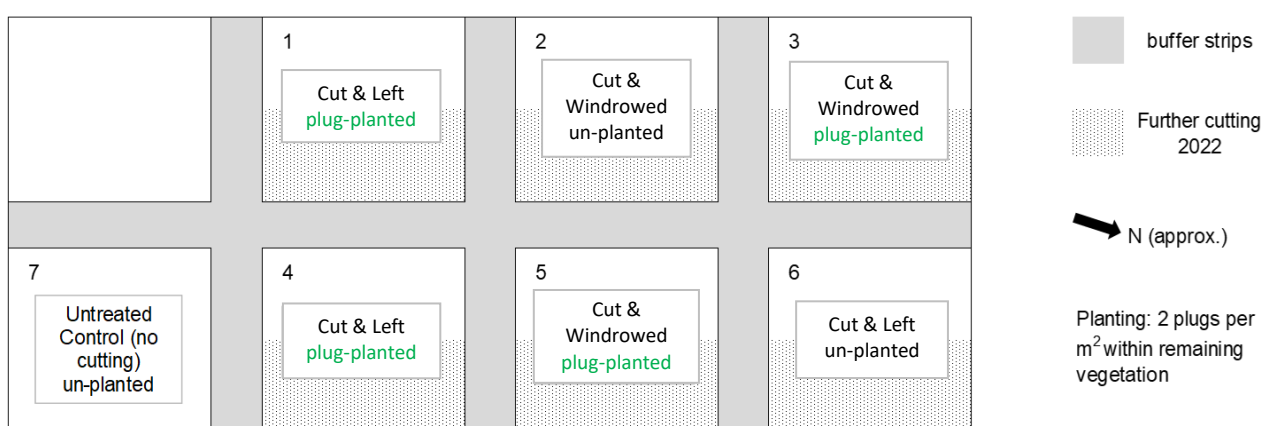


Figure 4. Trial plot arrangement.

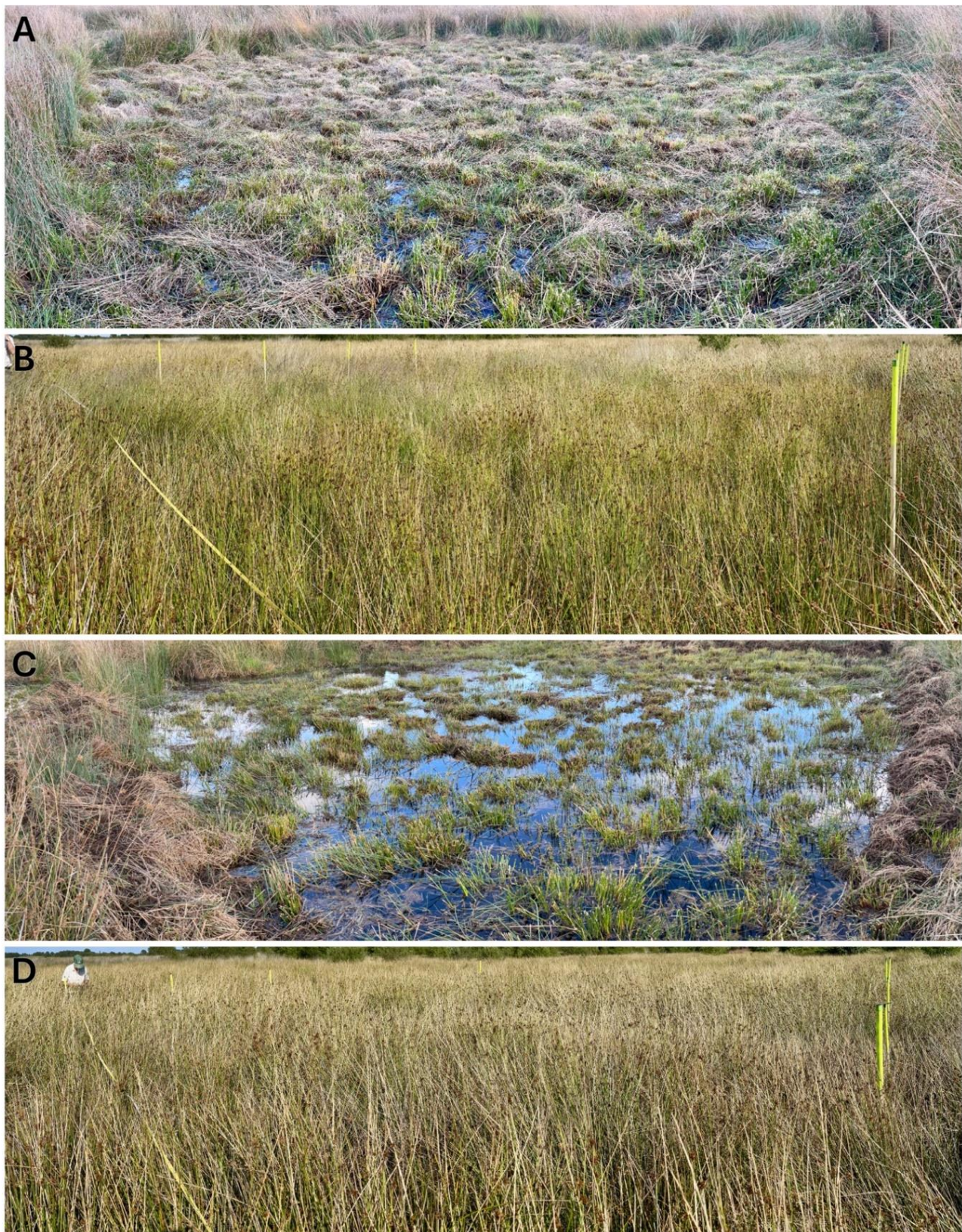


Figure 5. Example plot photos taken from the northwest corner of the plot in each case. The plots are: Cut and Left (Plot 1) after first *Juncus* cuts in Oct 2021 (A) and at monitoring in Aug 2022 (B); Cut and Windrowed (Plot 2) with deep standing water in Oct 2021 (C); and Untreated Control (D) at monitoring in Aug 2022.

conductivity (EC) and oxidation-reduction potential (ORP) (Haraguchi 1991, Rydin & Jeglum 2013) at five points in each treatment plot, four towards each corner and one centrally. Peat depth was measured using threaded rods; pH, EC and ORP were measured by digging a small slot in the peat with a spade, allowing it to infill with peat water, and inserting portable meters directly into the substrate until measurements settled. Meters used were a Hanna Instruments low reading conductivity meter HI98311 and a Hanna Instruments HI98121 combo-meter (ORP/pH). To record peat quality, one spade-depth example per plot was photographed (Figure 6D).

Statistical analysis

Statistical analysis was performed in R (v4.2.3) (R Core Team 2025) using Rstudio (v2025.05.1+513) (RStudio Team 2025). Comparisons between the distribution of measurements of *Sphagnum* and *Juncus* within treatment groups were performed

using permutational analysis of variance (PERMANOVA) (Anderson 2017), employing the ‘adonis2’ function in package ‘vegan’ (Oksanen *et al.* 2013) using a Jaccard distance matrix containing the data from all four measured variables with 999 permutations. Repeat sampling (in 2022 and 2024) and the spatial association of sub-plots within treatment plots (1–7) were managed by restricting permutations within a nested design (Simpson 2012), employing the ‘how’ function in package ‘permute’ (Simpson *et al.* 2016). Overall results were reported for the interaction of *Sphagnum* patch area or number of patches, and *Juncus* height or area cover with different planting, cutting and windrowing treatments with repeat measurements. Subsequent testing was performed to compare subsets of the data using the nested PERMANOVA structure. Mean measurements of *Sphagnum* and *Juncus* were calculated for each individual plot and combined to give overall means and standard deviations.



Figure 6. A–C: examples of *Sphagnum* patches within *Juncus* treatments observed at monitoring in August 2022 (A; dry) and November 2024 (B with good growth, C etiolated). D shows a peat profile to spade depth with surface layer of cut *Juncus* (left side) overlying a mix of peat, sand and clay.

RESULTS

Environmental measurements and observations

The average peat depth across all plots was 62.8 ± 22.7 cm (mean $\pm$ SD) with obvious inclusions of sand and clay due to mechanical turning of shallow peat into the substrate post-peat-extraction (Figure 6D). However, pH was surprisingly low at 3.9 ± 0.2 , with an ORP of 151 ± 56 mV and EC at 92 ± 15.6 $\mu\text{S cm}^{-1}$ (Table 1).

Water table measurements were reasonably stable (Figure 7) apart from brief falls during the summer months and a prolonged dry spell during summer 2022. A drainage pipe installed in the bund (B–B in Figure 3) effectively limited winter flooding to +5 cm.

There was no standing water on any of the plots in August 2022 due to a persistent lack of rainfall over the summer months which reflected weather conditions across the whole of the UK. Although there was still some moisture below the *Juncus* litter, the *Sphagnum* material was generally dry (Figure 6A) and identification of species could not be reliably undertaken. In November 2024, mean standing water across all plots was 44.3 ± 33.6 % at a mean depth of 6.4 ± 6.7 cm with the greatest cover and depth in the UTC plot (Table 1). *Sphagnum* had developed considerably over the study period (Figure 6B), with all species from the original mix apart from *S. denticulatum* seen, although it tended to be etiolated (Figure 6C).

Table 1. Comparisons between treatments and monitoring visits (values are means of sub-plot data where $n = 50$). Treatment plots: 10×10 m; vegetation measurements (both years) and water depth (2024) $n = 50$; water depth (at planting) $n = 9$; peat depth, pH, EC and RP $n = 5$. Untreated Control: 10×10 m; no *Juncus*-cutting or *Sphagnum* introduction. *Sphagnum* in unplanted and Untreated Control plots is likely to have been washed in with surface water from surrounding areas. EC = electrical conductivity in microSiemens per cm; ORP = oxidation/reduction (redox) potential, measured in millivolts. BP = Before Planting; NM = Not Measured.

<i>Juncus</i> treatment		Cut & Left			Cut & Windrowed			Untreated Control
Plot No.		1	4	6	3	5	2	7
<i>Sphagnum</i> plug-planted		Yes	Yes	No	Yes	Yes	No	No
Mean <i>Juncus</i> height (cm)	2022	74.4	75.5	81.3	65.8	67.6	76.6	121.4
	2024	98.2	102.3	96.1	103.1	105.1	106.7	109.9
Mean <i>Juncus</i> cover (1–4)	2022	3.2	2.7	2.5	2.2	2.6	2.5	3.9
	2024	3.6	3.8	3.2	3.5	3.6	3.6	3.7
Total <i>Sphagnum</i> area (m^2)	2022	0.83	0.51	0.00	1.62	1.20	0.16	3.95
	2024	2.70	2.23	0.00	12.70	3.46	1.97	4.27
<i>Sphagnum</i> patches (No.)	2022	81	86	0	103	79	6	9
	2024	50	38	0	108	55	10	13
Mean water depth (cm)	BP	5.9	3.7	5.0	14.3	4.2	16.3	NM
	2024	2.4	4.9	2.2	8.5	3.6	10.0	13.6
Mean water cover (%)	2024	32.7	41.4	13.9	51.7	37.1	64.2	69.4
Mean peat depth (cm)	2024	35.8	70.4	49.2	44.3	61.4	50.7	69.3
Mean pH	2024	4.0	3.8	3.8	3.7	3.8	4.0	4.0
Mean EC ($\mu\text{S cm}^{-1}$)	2024	113.2	91.2	90.6	90.0	84.8	85.8	88.4
Mean ORP (mV)	2024	131.0	170.0	144.0	172.8	159.4	62.8	198.8

Juncus height and cover

Across the two monitoring years of the trial (2022–2024), there were no significant differences in *Juncus* height ($p = 0.278$) or *Juncus* cover ($p = 0.232$) between all treatment plots (AT) and the untreated control plot (UTC) (Table A1 in the Appendix). However, there was a significant difference in *Juncus* height between UTC and AT in 2022 ($p = 0.004$) (UTC 121.4 ± 0.0 , AT 73.5 ± 5.8) but not in 2024 ($p = 0.735$) (UTC 109.9 ± 0.0 , AT 101.9 ± 4.1). There was no significant difference in *Juncus* cover between UTC and AT in 2022 ($p = 0.142$) (UTC 3.9 ± 0.0 , AT 2.6 ± 0.3) but a small significant difference in 2024 ($p < 0.001$) (UTC 3.7 ± 0.0 , AT 3.6 ± 0.2).

Overall, the *Juncus* management treatments did not achieve a lasting reduction in the vigour of *Juncus* tussocks, with the sward regrowing fully following cutting. The summers of 2023 and 2024 were wet (Figure 7), and *Juncus* height increased significantly between the 2022 and 2024 measurements ($p = 0.003$) (73.5 ± 5.8 cm; 101.8 ± 4.1 cm). *Juncus* cover also increased (2.6 ± 0.3 ; 3.6 ± 0.2), although this change was not statistically significant ($p = 0.203$).

There was no significant difference in *Juncus* height between PP and UP treatments in 2022 ($p = 0.054$) (PP 70.8 ± 4.9 cm; UP 78.9 ± 3.3 cm) or 2024 ($p = 0.425$) (PP 102.1 ± 2.9 cm; UP 101.4 ± 7.5 cm).

In 2022, there was no significant difference in *Juncus* height ($p = 0.768$) between cutting treatments (1C&L 77.1 ± 3.7 cm; 1C&W 70.0 ± 5.8 cm). In

2024, there was a small but significant difference in *Juncus* height between areas not receiving a second cut ($p = 0.044$) (2U.C&L 97.4 ± 0.4 cm; 2U.C&W 103.4 ± 1.9 cm), and also in areas that received a second cut ($p = 0.005$) (2C&L 100.3 ± 6.2 cm; 2C&W 106.4 ± 1.9 cm). There was no significant difference in *Juncus* height between 2C&L and 2U.C&L ($p = 0.139$) or between 2C&W and 2U.C&W ($p = 0.078$).

There was no significant difference in *Juncus* cover between PP and UP treatments in 2022 ($p = 0.415$) (PP 2.7 ± 0.4 ; UP 2.5 ± 0.0) or 2024 (PP 3.6 ± 0.2 ; UP 3.4 ± 0.3).

In 2022 there was no significant difference in *Juncus* cover ($p = 0.513$) between cutting treatments (1C&L 2.8 ± 0.3 ; 1C&W 2.5 ± 0.2). In 2024, there was no significant difference in *Juncus* cover between treatment areas not receiving a second cut ($p = 0.259$) (2U.C&L 3.6 ± 0.5 ; 2U.C&W 3.7 ± 0.2 cm), and a small but significant difference in *Juncus* cover between treatment areas that received a second cut ($p = 0.012$) (2C&L 3.5 ± 0.4 cm; 2C&W 3.4 ± 0.2 cm). There were no significant differences in *Juncus* cover between 2C&L and 2U.C&L ($p = 0.957$) or 2C&W and 2U.C&W ($p = 0.720$). As there was no difference in *Juncus* height or cover between plug planted (PP) and unplanted (UP) treatments plots, there is no evidence that the addition of *Sphagnum* had any overall influence on *Juncus* vigour at this very early stage of *Sphagnum* colonisation.

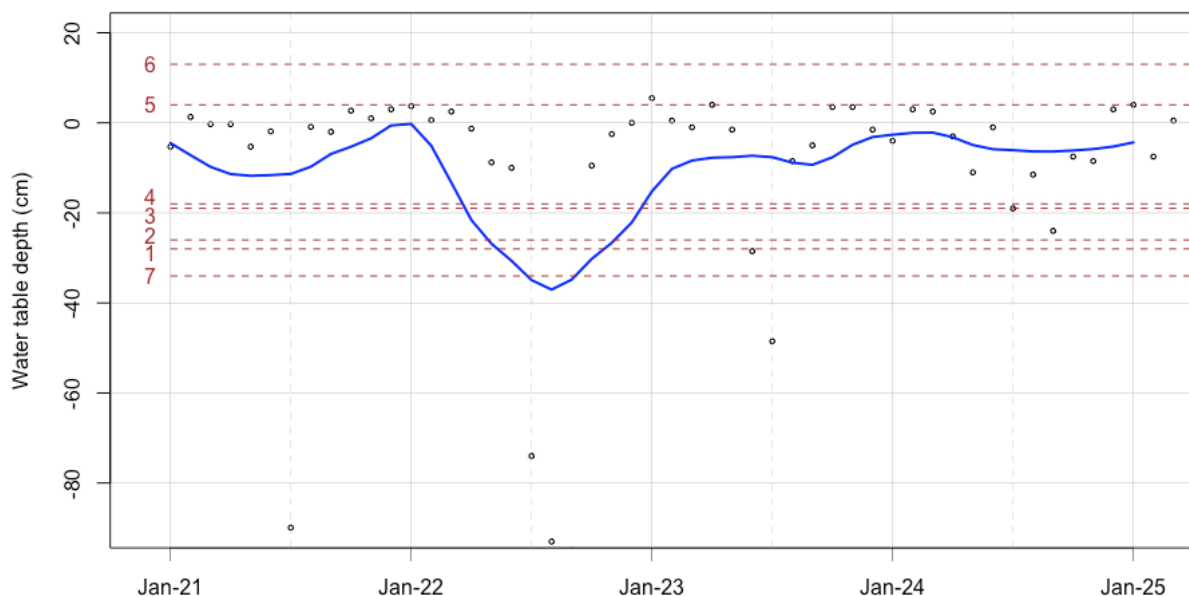


Figure 7. Water table depths recorded monthly during the trial period with the smoothed trendline (Locally Estimated Scatterplot Smoothing) shown in blue. The relative elevation of the centre of each trial plot (1 to 7) is shown in brown, although the elevation of areas within each trial plot varied significantly (Figure 3). Most areas were seasonally flooded, although some areas were permanently above water and others were flooded throughout most of the trial period.

Sphagnum patch area and number

Across the two monitoring years of the trial (2022 to 2024) there were significant differences in the area ($p = 0.001$) and number ($p = 0.015$) of *Sphagnum* patches between AT plots and the UTC plot. The total cover of *Sphagnum* within AT plots was 4.3 m² (0.7 %) in 2022, increasing to 23.2 m² (3.9 %) in 2024. The cover of *Sphagnum* in the UTC plot (extraneous aquatic *Sphagnum*, likely to have been present prior to the experiment, washed in from the surrounding area) was 4.0 m² (4.0 %) in 2022, increasing to 4.3 m² (4.3 %) in 2024.

The percentage cover of *Sphagnum* for the planted treatments in 2022 and 2024 respectively were C&L: 0.67 % and 2.46 % and C&W: 1.41 % and 8.08 % ; i.e., there was an increase in *Sphagnum* cover of 1.79 % in the C&L treatment and of 6.67 % in the C&W treatment. The existing *Sphagnum* in 2022 and 2024 respectively in the C&W unplanted treatment was 0.16 % and 1.97 % (increase of 1.81 %) and there was no *Sphagnum* in the C&L unplanted treatment in either year. In 2022 it appeared that 80 %

or more of the plugs had survived, but by 2024 the mean number had reduced in both C&L (0.88 ± 1.02) and C&W plots (1.68 ± 1.26). It is notable that the largest number and area of patches in planted treatments, in both monitoring years, was in the C&W plot 3 which had the deepest standing water at both time of planting and 2024 monitoring (Table 1).

The effect on *Sphagnum* patch area and patch number predicted by the various cutting treatments applied to AT plots were compared in a more specific analysis to address Research Questions (1), (3) and (4). The UTC plot, which had a large amount of aquatic *Sphagnum*, (Research Question 2) was excluded from this part of the analysis (Table A1).

Sphagnum patch area

There was a large and statistically significant increase in the distribution of *Sphagnum* patch areas in AT (combined PP and UP, all treatment) plots ($p < 0.001$) between 2022 (144.2 ± 124.3 cm²) and 2024 (774.3 ± 911.3 cm²) (Figure 8H). In 2022 there was significantly greater *Sphagnum* patch area

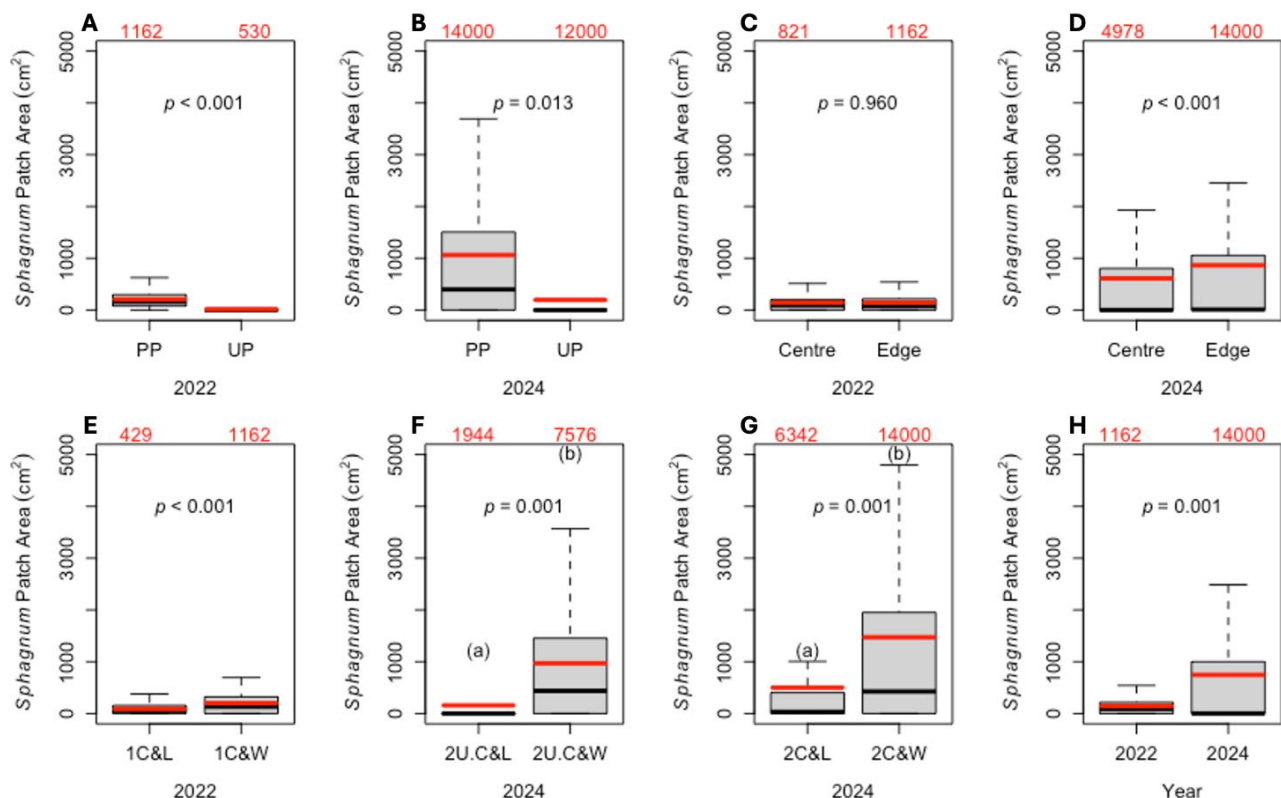


Figure 8. Boxplots showing *Sphagnum* patch areas in relation to treatment regimes. Maximum patch areas (red numbers), mean measurements (red horizontal lines) and median measurements (black horizontal lines) are shown. (A) and (B) compare planted (PP) and unplanted (UP) plots in each monitoring year; (C) and (D) compare centre and edge areas of combined treatment plots in each monitoring year; (E) compares first cut and left (1C&L) and first cut and windrowed (1C&W) treatments in 2022; (F) compares C&L and C&W treatments in 2024 without the 2nd cutting; (G) compares C&L and C&W treatments in 2024 after the 2nd cutting; (a-a) $p = 0.001$; (b-b) $p = 0.001$.; (H) shows overall change in patch area across all treatments.

($p < 0.001$) in all plug-planted (PP) plots ($208.2 \pm 95.9 \text{ cm}^2$) than in all unplanted (UP) plots ($16.3 \pm 23.0 \text{ cm}^2$) (Figure 8A), and in 2024 there was significantly greater ($p = 0.013$) *Sphagnum* patch area in all PP plots ($1062.9 \pm 1012.4 \text{ cm}^2$) than in all UP plots ($196.9 \pm 278.5 \text{ cm}^2$) (Figure 8B). The high standard deviation values, particularly in 2024, demonstrate the wide size range of patches.

Overall, there were significant differences in *Sphagnum* patch area (combined PP and UP plots) between cutting treatments ($p < 0.001$). In 2022 there was significantly greater *Sphagnum* patch area ($p < 0.001$) in C&W plots ($199.3 \pm 150.2 \text{ cm}^2$) than in C&L plots ($89.2 \pm 83.5 \text{ cm}^2$) (Figure 8E), and in 2024 there was significantly greater *Sphagnum* patch area ($p < 0.001$) in C&W plots ($1220.1 \pm 1181.9 \text{ cm}^2$) than in C&L plots ($328.4 \pm 288.2 \text{ cm}^2$) (Figures 8F and 8G).

In 2024, there were significant differences in *Sphagnum* patch area ($p < 0.001$) between west (no 2nd cut) and east (with 2nd cut) sides of all treatment plots. There were significant differences in

Sphagnum patch area between treatments without a 2nd cut ($p < 0.001$): 2U.C&W ($969.1 \pm 961.0 \text{ cm}^2$) and 2U.C&L (157.5 ± 169.6) (Figure 8F). *Sphagnum* patch area was significantly greater ($p < 0.001$) following repeated cutting and windrowing (2C&W; $1471.2 \pm 1532.1 \text{ cm}^2$) than with repeated cutting and leaving (2C&L; $499.4 \pm 432.5 \text{ cm}^2$) (Figure 8G). There were also significant differences in *Sphagnum* patch area between 2C&W and 2U.C&W ($p < 0.001$), and 2C&L and 2U.C&L ($p < 0.001$) (Figures 8F and 8G). The best result was achieved with repeated cutting and windrowing treatments.

Sphagnum patch number

There was a large and statistically significant reduction in the distribution of *Sphagnum* patch numbers in AT (combined PP and UP, all treatment) plots ($p = 0.001$) between 2022 (1.2 ± 0.9) and 2024 (0.9 ± 0.8) (Figure 9H). There were significantly more *Sphagnum* patches ($p < 0.001$) in PP plots than in UP plots in both 2022 (Figure 9A) and 2024 (Figure 9B).

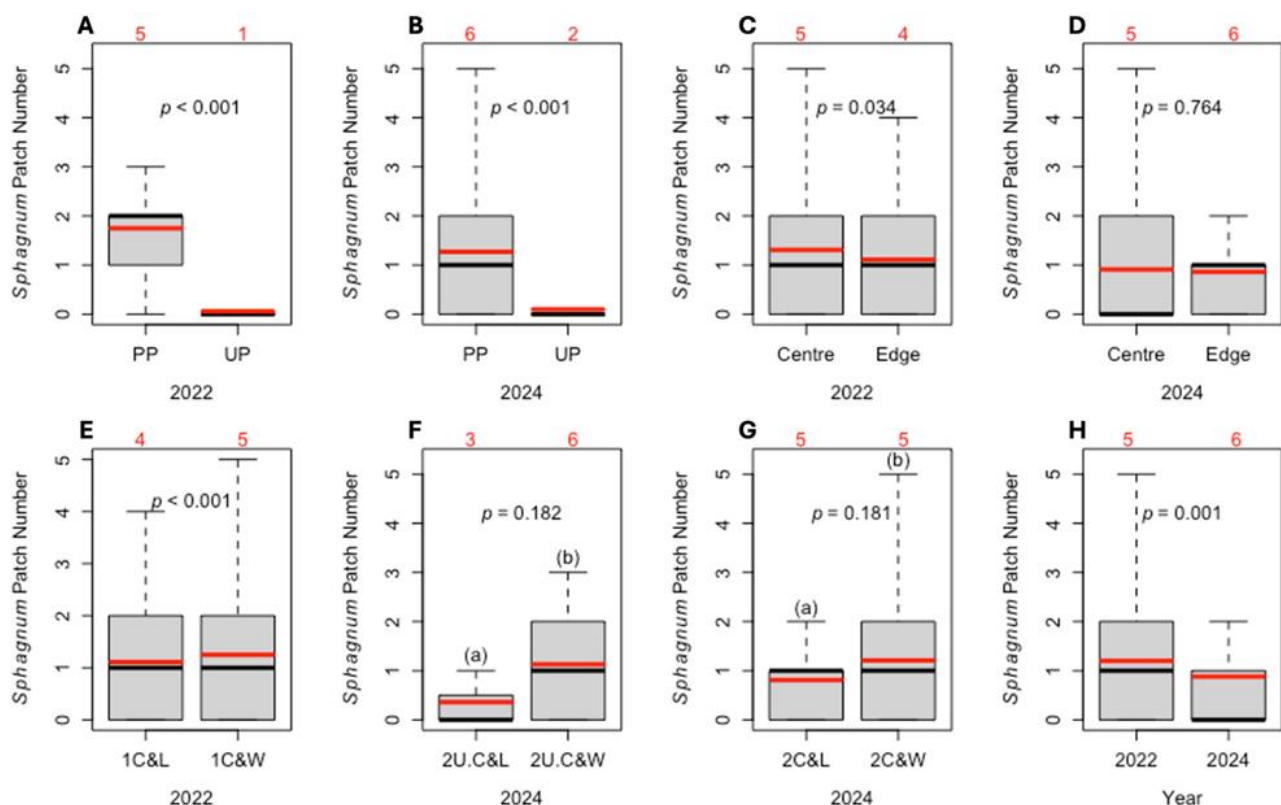


Figure 9. Boxplots showing *Sphagnum* patch numbers in relation to treatment regimes. Maximum numbers of patches (red numbers), mean measurements (red horizontal lines) and median measurements (black horizontal lines) are shown. (A) and (B) compare planted (PP) and unplanted (UP) plots in each monitoring year; (C) and (D) compare centre and edge areas of combined treatment plots in each monitoring year; (E) compares first cut and left (1C&L) and first cut and windrowed (1C&W) treatments in 2022; (F) compares C&L and C&W treatments in 2024 without the 2nd cutting; (G) compares C&L and C&W treatments in 2024 with the 2nd cutting; (a-a) $p = 0.090$; (b-b) $p = 0.174$; (H) shows overall change in number of patches across all treatments.

In 2022 there was a minimal but statistically significant difference in the number of *Sphagnum* patches ($p < 0.001$) between the C&W (1.25 ± 1.0) and C&L (1.1 ± 1.0) plots (PP and UP combined) (Figure 9E), but in 2024 there were no statistically significant differences throughout (Figures 9F and 9G).

Plot edge effects

Potential differences related to an edge effect were assessed and found to be generally negligible. Any small differences in *Juncus* height between edge and centre in treatment plots were not statistically significant in both monitoring years, and a small difference in the UTC plot (Centre > Edge) was due to an old ditch running through the centre of the plot, lowering the ground level while the top of the *Juncus* sward was even. There was a small but statistically significant difference ($p = 0.004$) in *Juncus* cover between centre and edge areas in 2022 (centre 2.6 ± 0.3 ; edge 2.67 ± 0.4), but no other significant differences throughout.

Overall, there were small but statistically significant differences in *Sphagnum* patch areas ($p < 0.001$) between the centre and edge of plots, although these were inconsistent between 2022 ($p = 0.960$) (centre $145.0 \pm 131.0 \text{ cm}^2$; edge $143.8 \pm 124.2 \text{ cm}^2$) and 2024 ($p < 0.001$) (centre $614.0 \pm 713.3 \text{ cm}^2$; edge $864.4 \pm 1029.3 \text{ cm}^2$) (Figures 8C and 8D).

In 2022 there was a small but statistically significant difference in the number of *Sphagnum* patches ($p = 0.034$) between the centre (1.3 ± 1.0) and edge (1.1 ± 0.8) of plots; however, in 2024 the difference was not statistically significantly ($p = 0.764$) (Figures 9C & 9D).

Other species

The species that made up the majority of other plants found within plots in 2022 were *Molinia caerulea*, *Holcus lanatus* and pleurocarpous ('feather') mosses (Table A2). Other species seen regularly in the drier plots were *Betula* species, *Epilobium*-type species and ferns. There was a lower incidence of some of the forbs in the C&W plots, but otherwise very little difference overall between treatments. Growth of most other species, apart from feather mosses and *Epilobium*-type species was precluded in the UTC plot, where the *Juncus* was tall and dense and the in-situ plant litter was approximately 20 cm deep. In 2024, *Betula* sp. increased in the drier plots and reduced in the wettest plot, *M. caerulea* increased in the driest plot and reduced elsewhere, *H. lanatus* had disappeared or greatly reduced throughout, perhaps due to wetter conditions, as had some other forbs that are usually related to drier conditions. More liverwort

was seen, and *Polytrichum commune* appeared where the water levels were mid-range. Species diversity in the UTC plot remained lower than elsewhere.

Water Vole (*Arvicola amphibius*) feeding signs, but no latrines, were seen fairly regularly across the plots.

DISCUSSION

Juncus effusus (*Juncus*) in treatment plots was cut twice in 2021 prior to planting *Sphagnum*, and the eastern half of each plot was cut again after the first survey visit in 2022, with a final survey in 2024. Uncut *Juncus* (UTC) was taller than *Juncus* under cutting treatments when surveyed in 2022, but the height and density of *Juncus* returned to pre-cut levels in treatments by 2024, despite a 2nd cut in half of the plots. Initially, cutting and windrowing (C&W) appeared to reduce height and cover more than cutting and leaving the cut stems in place (C&L), but there was no evidence of this at the final survey, perhaps due to removal of nutrients and then increased access to light separately influencing *Juncus* growth. The further cut in the eastern half of each treatment plot one year after the initial cuts did not result in a lower sward than in the western half after two years. A lasting depression in *Juncus effusus* growth, or even elimination of the plant, can only be achieved by regular mowing which both sufficiently damages the plant (Gaudig *et al.* 2017) and precludes seed germination through light competition from other plants (Lazenby 1955). Certainly, more regular cutting than in this trial was needed to reduce *Juncus* dominance, despite *Sphagnum* introduction (Research Question 1) (McCorry & Renou 2003, Gaudig *et al.* 2017). A slight reduction in height of *Juncus* in the uncut treatment may be related to trampling damage during the initial survey, but this would have been so for all of the plots.

Despite the peat mineral content, the pH was surprisingly low and typical for a bog, but also, along with the ORP level, indicates continually waterlogged/anaerobic conditions (Haraguchi 1991) albeit this was measured in November. EC was higher than on the neighbouring Cadishead Moss ($45.46 \pm 4.54 \mu\text{S cm}^{-1}$) (Keightley *et al.* 2023) where peat is deeper, fully organic and supports typical bog vegetation. Nutrients in the trial area are currently being consumed by the *Juncus*, judging by its high biomass (Meuleman *et al.* 2002), but are likely to persist once *Juncus* dominance is reduced unless replaced by a variety of substitute nutrient-demanding plants, which would include *Sphagnum*. Other vascular plant species recorded were limited in

diversity and related to local moisture levels, although most were precluded within the undisturbed, dense *Juncus* in the UTC plot. Reducing the *Juncus* dominance would allow the habitat to be more floristically diverse, perhaps developing into a fen which, considering the benefits of fen biodiversity (JNCC 2016) and carbon sequestration potential (Schwieger *et al.* 2021), would be a positive outcome, although creation of a functioning fen is not straightforward (Khan *et al.* 2025).

The existing *Sphagnum* area in the UTC plot expanded very little over the two years of monitoring (Research Question 2), likely due to lack of light, and probably only establishes through being washed in from elsewhere. However, the lack of *Sphagnum* expansion in the UTC plot could also be related to the species (*S. cuspidatum*: Ellenberg values of L = 8, F = 10, R = 1, N = 2) which requires (and received) high moisture levels but also good access to light (Hill *et al.* 2007). The existing *Sphagnum* area in the C&W treatment plot (species seen: *S. cuspidatum*, *S. fallax*, *S. fimbriatum*, *S. palustre*) expanded far more than in the UTC plot over the two years. It appeared that cutting *Juncus*, even occasionally, was beneficial for *Sphagnum* proliferation (Research Question 3) because of greater access to light and perhaps improved nutrient supply when uptake by *Juncus* was interrupted. There was no existing *Sphagnum* in the unplanted C&L plot (Plot 6) throughout, suggesting that *Sphagnum* will not naturally colonise in *Juncus*-dominated areas, despite more favourable conditions, unless perhaps it is transported aquatically. This plot was higher in elevation than some other plots, but had standing water in each year this was measured, and generalised flooding across the site during wetter months of the year was likely to facilitate *Sphagnum* wash-in if available locally.

Initial plug survival was around 80 % or more across all planted plots, but overall there was an increase in patch area and a decrease in number of patches over the study period. It is likely that *Sphagnum* material drifted during times of flooding, which gave different numbers of patches per plot and which differed more over time. Loose material may have joined other material or created separate patches, or been lost entirely. It is of note that the largest number and area of patches in planted treatments, in both monitoring years, had the deepest standing water at the time of planting and at 2024 monitoring, so perhaps the *Sphagnum* had not dehydrated as much as in other plots during the 2022 dry period, supporting continued growth (Hájek 2013).

There was more *Sphagnum* in planted than in unplanted treatment plots. The best *Sphagnum*

growth was associated with areas of greater light accessibility, and the greatest *Sphagnum* cover was in the C&W plots. The mean *Sphagnum* patch size was larger in C&W than in C&L treatments in both survey years, and the increase in total percentage cover of *Sphagnum* in C&W treatments was four times greater than that in C&L treatments over the study period. This demonstrated that the C&L treatment probably smothered the *Sphagnum* with *Juncus* litter (Malmer *et al.* 1994), reducing light availability, and that the C&W treatment better supports *Sphagnum* establishment and growth rate. Additionally, there is better growth in larger than in smaller *Sphagnum* patches due to 'positive self-association' (Robroek *et al.* 2009). Moreover, the existing *Sphagnum* in the C&W unplanted plot expanded more than in the C&L planted plot, showing that leaving the cut *Juncus* material in place reduces the benefits of cutting. The minimal relationships between *Sphagnum* area in the cut treatments and *Juncus* height and cover highlights that management of the cut material is the dominant factor in supporting *Sphagnum* growth (Research Question 4). Although the *Juncus* regrew after cutting, the second cut in half of each treatment plot periodically allowed light access and appeared to promote *Sphagnum* growth. However, leaving the cut material to potentially provide some environmental protection for *Sphagnum* after initial exposure post-cutting, as is beneficial on nutrient-poor, bare peat sites (Pouliot *et al.* 2011), was not beneficial in this scenario. Additionally, *Sphagnum* had become etiolated over time due to shading, which is likely to promote drying through exposure in drought periods, hamper photosynthetic ability (slowing growth) or even cause loss of material (Aerts *et al.* 2001, Hájek 2013, Rydin & Jeglum 2013). Therefore, additional cutting would be of long-term benefit to *Sphagnum* proliferation.

More regular cutting would keep *Juncus* height lower (as demonstrated in the first monitoring year) and may also allow cut material to be left in place over time, as a decreasing amount of material would smother the *Sphagnum* less on each occasion. Therefore, a plausible approach to reducing *Juncus effusus* where it is dominant on restoration peatlands, in favour of *Sphagnum* growth, is to cut and windrow *Juncus* twice prior to *Sphagnum* planting, then cut the *Juncus* regularly thereafter, perhaps twice yearly. To reduce effort and time, the cut material could then be left in place, as a smaller amount of material would be less likely to smother developing *Sphagnum*. *Juncus* would then weaken naturally over time, but provide a scaffold, anchor and some environmental protection for *Sphagnum* (Pouliot *et al.* 2011, Telgenkamp *et al.* 2025) as it establishes and then

eventually dominates the area. There are, of course, constraints to intensive management of this nature, even by mechanical means, as resources are often stretched across several sites, projects or additional sites, and a balance of overall best outcomes has to be assessed.

The windrowed material, on observation, did not appear to support many other plant species, contrary to the previous trial where there was substantial colonisation of feather mosses, but it may be a refugium for other wildlife. It was anticipated that the windrowed material would also keep the edges of those plots more open, allowing *Sphagnum* greater light access to benefit growth, but was not the case, and by 2024 the windrowed material was no longer evident. However, species diversity on treatment plots was higher than in the UTC plot, evidencing a biodiversity gain from cutting *Juncus* and allowing access for wind-blown seed, increased light availability and perhaps access to nutrients from *Juncus* material after cutting. Evidence of Water Vole activity was seen on the trial area, and as this is a protected species in the UK under the Wildlife and Countryside Act 1981 a full survey should be carried out to look for evidence of Water Vole presence or activity prior to undertaking any surveys or cutting regimes on inundated *Juncus*-dominated areas.

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AUTHOR CONTRIBUTIONS

AK undertook field recording, wrote the first draft, edited subsequent drafts, managed the data, and is the lead author; AO undertook all mapping and statistical analysis, and edited drafts; AO and TR undertook field surveying; all authors originated and planned the work, undertook site selection and fieldwork, and approved the final draft.

DATA AVAILABILITY

Keightley, Anna (2025), “Raw data - Keightley et al. 2025 Cutting *Juncus*”, Mendeley Data, V1, doi: 10.17632/zc3gp99yf2.1

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Appendix

Table A1. All statistical analysis results using sub-plot values. AT = all treatments; UTC = untreated control; J = *Juncus*; Sph = *Sphagnum*; Cover = area of *Sphagnum* patches; Patches = number of patches; PP = plug-planted; UP = unplanted; E = within edges of plots; C = at centres of plots; Year = monitoring year; C&W = cut and windrowed *Juncus* treatment; C&L = cut and left *Juncus* treatment; 1, 2 or 2U. = 1st cuts, 2nd cuts or 2nd year uncut treatments; JHeight = height of majority of *Juncus* within sub-plot; JCover = estimated *Juncus* cover on a 1 (least dense) to 4 (most dense) scale (see Methods).

Years : Subgroups	Interacting Predictor Variables	df	Sum of Squares	R ²	F	p.value
<i>AT-UTC: Overall Comparisons</i>						
2022–2024	JHeight:AT-UTC:Year	1	0.469	0.003	2.507	<i>p</i> = 0.278
2022–2024	JCover:AT-UTC:Year	1	0.205	0.001	1.055	<i>p</i> = 0.232
2022–2024	SphCover:AT-UTC:Year	1	21.412	0.136	175.191	<i>p</i> = 0.001
2022–2024	SphPatches:AT-UTC:Year	1	0.480	0.003	4.581	<i>p</i> = 0.015
<i>AT Plots: Comparisons of Sphagnum Cover</i>						
2022–2024	SphCover:Year	1	22.678	0.167	171.583	<i>p</i> = 0.001
2022	SphCover:PP-UP	1	0.811	0.015	12.758	<i>p</i> < 0.001
2024	SphCover: PP-UP	1	0.728	0.010	4.957	<i>p</i> = 0.013
2022–2024	SphCover:E-C:Year	1	0.063	0.000	0.493	<i>p</i> = 0.690
2022	SphCover:E-C	1	0.017	0.000	0.192	<i>p</i> = 0.960
2024	SphCover:E-C	1	3.295	0.046	20.113	<i>p</i> < 0.001
2022–2024	SphCover:1C&W-1C&L:Year	1	3.776	0.028	32.522	<i>p</i> < 0.001
2022	SphCover:1C&W-1C&L	1	4.131	0.079	55.056	<i>p</i> < 0.001
2024	SphCover:2C&W-2C&L	3	7.245	0.101	16.769	<i>p</i> < 0.001
2024:2C	SphCover:2C&W-2C&L	1	2.265	0.060	12.603	<i>p</i> = 0.001
2024:2U	SphCover:2U.C&W-2U.C&L	1	2.199	0.068	20.311	<i>p</i> = 0.001
2024:2C/U	SphCover:2C&W-2U.C&W	1	2.265	0.057	12.377	<i>p</i> = 0.001
2024:2C/U	SphCover:2C&L-2U.C&L	1	1.578	0.058	15.020	<i>p</i> = 0.001
<i>AT Plots: Comparisons of Sphagnum Patches</i>						
2022–2024	SphPatches:Year	1	8.029	0.059	71.309	<i>p</i> = 0.001
2022	SphPatches:PP-UP	1	1.358	0.026	17.693	<i>p</i> < 0.001
2024	SphPatches:PP-UP	1	1.217	0.017	9.471	<i>p</i> < 0.001
2022–2024	SphPatches:E-C:Year	1	0.129	0.001	0.881	<i>p</i> = 0.344
2022	SphPatches:E-C	1	0.185	0.004	2.105	<i>p</i> = 0.034
2024	SphPatches:E-C	1	0.056	0.001	0.407	<i>p</i> = 0.764

Years : Subgroups	Interacting Predictor Variables	<i>df</i>	Sum of Squares	<i>R</i> ²	<i>F</i>	<i>p</i> .value
<i>AT Plots: Comparisons of Sphagnum Patches (continued)</i>						
2022–2024	SphPatches:1C&W-1C&L:Year	1	1.107	0.008	10.471	<i>p</i> = 0.001
2022	SphPatches:1C&W-1C&L	1	1.003	0.019	12.550	<i>p</i> < 0.001
2024	SphPatches:2C&W-2C&L	3	1.426	0.020	3.642	<i>p</i> < 0.001
2024:2C	SphPatches:2C&W-2C&L	1	0.593	0.016	3.791	<i>p</i> = 0.181
2024:2U	SphPatches:2U.C&W-2U.C&L	1	0.565	0.017	5.395	<i>p</i> = 0.182
2024:2C/U	SphPatches:2C&W-2U.C&W	1	0.238	0.006	1.466	<i>p</i> = 0.174
2024:2C/U	SphPatches:2C&L-2U.C&L	1	0.251	0.009	2.553	<i>p</i> = 0.090
<i>AT Plots: Comparisons of Juncus Height</i>						
2022–2024	JHeight:Year	1	4.925	0.036	25.465	<i>p</i> = 0.003
2022	JHeight:PP-UP	1	0.290	0.006	2.729	<i>p</i> = 0.054
2024	JHeight:PP-UP	1	0.127	0.002	0.663	<i>p</i> = 0.425
2022	JHeight:E-C	1	0.234	0.004	1.520	<i>p</i> = 0.555
2024	JHeight:E-C	1	0.097	0.001	0.415	<i>p</i> = 0.706
2022	JHeight:1C&W-1C&L	1	0.296	0.006	1.964	<i>p</i> = 0.768
2024:2C	JHeight:2C&W-2C&L	1	1.943	0.051	8.421	<i>p</i> = 0.005
2024:2U	JHeight:2U.C&W-2U.C&L	1	0.553	0.017	3.018	<i>p</i> = 0.044
2024:2C/U	JHeight:2C&W-2U.C&W	1	0.436	0.011	1.717	<i>p</i> = 0.078
2024:2C/U	JHeight:2C&L-2U.C&L	1	0.369	0.014	2.306	<i>p</i> = 0.139
<i>AT Plots: Comparisons of Juncus Cover</i>						
2022–2024	JCover:Year	1	0.836	0.006	4.826	<i>p</i> = 0.861
2022	JCover:PP-UP	1	0.161	0.003	1.406	<i>p</i> = 0.415
2024	JCover:PP-UP	1	0.118	0.002	0.608	<i>p</i> = 0.072
2022	JCover:E-C	1	0.484	0.009	2.776	<i>p</i> = 0.004
2024	JCover:E-C	1	0.316	0.004	1.329	<i>p</i> = 0.591
2022	JCover:1C&W-1C&L	1	0.765	0.015	4.584	<i>p</i> = 0.513
2024:2C	JCover:2C&W-2C&L	1	0.714	0.019	2.941	<i>p</i> = 0.012
2024:2U	JCover:2U.C&W-2U.C&L	1	1.664	0.051	9.183	<i>p</i> = 0.259
2024:2C/U	JCover:2C&W-2U.C&W	1	0.413	0.010	1.625	<i>p</i> = 0.720
2024:2C/U	JCover:2C&L-2U.C&L	1	0.066	0.002	0.389	<i>p</i> = 0.957

Table A2. Percentage of sub-plots within each treatment plot where species other than *Juncus effusus* and *Sphagnum* were present. C&L = *Juncus* cut and left; C&W = *Juncus* cut and windrowed; PP = *Sphagnum* plug-planted; UP = unplanted; Untreated Control = no cutting or plug-planting; Ca = *Chamaenerion angustifolium*; NM = not measured.

Quadrat No.	1		4		6		3		5		2		7	
Treatment	C&L PP		C&L PP		C&L UP		C&W PP		C&W PP		C&W UP		Untreated Control	
Monitoring year	2022	2024	2022	2024	2022	2024	2022	2024	2022	2024	2022	2024	2022	2024
<i>Agrostis canina</i>	0	0	0	10	0	0	0	0	0	0	0	0	0	0
<i>Betula</i> sp.	6	2	18	16	14	28	14	17	14	26	12	2	0	0
<i>Epilobium</i> -type sp. (inc. Ca)	20	24	50	58	62	66	6	2	24	60	10	6	16	62
Feather moss	94	90	96	84	96	70	50	34	100	84	76	74	40	66
Fern	8	4	20	14	44	40	0	0	34	28	0	0	0	0
Fungi	0	2	6	2	0	2	0	0	0	0	0	0	2	0
<i>Holcus lanatus</i>	6	0	30	0	72	6	32	0	70	0	10	2	0	0
<i>Juncus bulbosus</i>	0	0	0	0	0	0	2	0	0	0	4	0	0	0
Liverworts	0	26	0	24	0	8	0	6	0	40	0	0	0	14
<i>Molinia caerulea</i>	80	68	20	18	36	76	34	21	24	20	56	34	4	4
<i>Polytrichum</i> sp.	0	0	0	4	0	2	0	0	0	2	0	0	0	0
<i>Rubus</i> sp.	0	0	0	0	0	2	0	0	0	0	0	0	0	0
<i>Rumex</i> sp.	0	0	2	0	22	2	8	0	4	0	0	0	0	0
<i>Salix</i> sp.	0	0	0	2	2	6	0	4	2	2	2	2	0	0
<i>Senecio</i> sp.	0	0	12	2	14	0	0	0	12	2	2	0	0	0
Other forbs	0	0	0	0	0	0	2	0	2	0	0	0	4	0
Mean water depth (cm)	NM	2.4	NM	4.9	NM	2.2	NM	8.5	NM	3.6	NM	10.0	NM	13.6
Mean surface water (%)	NM	32.7	NM	41.4	NM	13.9	NM	51.7	NM	37.1	NM	64.2	NM	69.4