Exploring the impact of mulching Purple Moor-grass (*Molinia caerulea*) on lowland raised bog restoration in Greater Manchester.

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Abstract

Peatlands are habitats for rare species, and valuable carbon sinks, however are threatened by anthropogenic activities. Lowland raised bogs are especially degraded from land-use, with restoration hindered by Purple moor-grass (*Molinia caerulea*) encroachment which dries out and enriches peat. Reducing *Molinia* dominance helps restore diversity and peat function to peatlands.

This study explores whether mulching vegetation reduces *Molinia* dominance and restores peatland function on damaged bogs. Mulching has been trialed on bogs degraded by drainage, peat-cutting and Molinia encroachment: vegetation is cut very low ('flailed') and the litter left on the peat surface. Three sampling sites in Greater Manchester were compared: one unmulched control to two sites mulched in Winter 2022/23. Vegetation surveys comparing plant communities focused on diversity, and the abundance of *Molinia* and wetland indicator species like *Sphagnum* mosses. Because hydrology controls wetland species distribution, the impact of differing water tables on vegetation was explored. At Rindle, peat samples were analysed for variables like bulk density and nutrients to explore the peat-vegetation interface.

Mulching reduced the dominance of *Molinia* at treated sites, increasing floristic diversity and wetland indicator species. However, low water table at Astley limited *Sphagnum* growth, while inundation at Rindle allowed *Sphagnum* to compete with *Molinia*. Raised bog vegetation requires a high water table, so mulching alone was not sufficient in restoring peat function. At Rindle, relationships between vegetation and nutrients indicated slowed decomposition and peat-forming processes, and *Molinia* increasing peat nutrients. Continued monitoring, and research further exploring the peat-water-vegetation interface is recommended.

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1 Introduction

Peatlands are important ecosystems, storing carbon and supporting rare species (Bain *et al.*, 2011), however are are at risk. Among the most degraded peatlands are raised bogs, which are rare and threatened by land-use pressures (Worrall *et al.*, 2011). Peat extraction and drainage have damaged and destroyed almost all UK lowland raised bogs (Moore, 2002). The encroachment of grasses like Purple moor-grass dries and enriches peat, preventing restoration (Meade, 2015). Reducing its dominance through methods like mulching may help bog restoration (Rosenburgh, 2015).

This study aims to explore the effects of mulching Purple moor-grass on restoration of degraded raised bog. Research questions are in section 2.4.6.

2 Academic context

2.1 Importance of peatlands

Peatlands are wetlands with a layer of peat made of carbon-rich decaying plant matter in waterlogged conditions. In the UK, it is primarily *Sphagnum* mosses that form peat (Bain *et al.*, 2011). Peatlands have an intrinsic value and right to flourish. They also provide countless "Ecosystem Services": benefits to people and society (Bonn *et al.*, 2016). Despite covering only 3% of the land surface, peatlands are vital carbon sinks, storing 30% of global soil carbon. Decomposition is slow due to anoxic waterlogged conditions and *Sphagnum* characteristics (Müller *et al.*, 2023), so organic matter accumulates, building peat that stores carbon removed from the atmosphere through photosynthesis. This unique vertical accumulation of matter (Minayeva *et al.*, 2017) means peatlands store seven times more carbon than other ecosystems (Bain *et al.*, 2011). While peatlands release methane, in the long-term they reduce greenhouse gases, mitigating climate change (Bain *et al.*, 2011).

Peatlands support specialised plants and animals, including rare mosses and invertebrates. These species are sensitive to environmental changes given their adaptations to acidic, waterlogged, nutrient-poor peatland (Bain *et al.*, 2011). Protecting biodiversity is important to maintain ecosystem resilience and allow organisms to thrive (Mooney *et al.*, 1996).

2.1.1 Raised bogs

Raised bogs are Special Areas of Conservation categorised as priority Annex I habitats under the EU Habitats Directive (92/43/EEC, 2013). Both 'Active raised bogs' and

‘Degraded raised bogs still capable of natural regeneration’ are included, because they are rare habitats and most European raised bogs have been damaged (JNCC, 2004).

Raised bogs start forming in shallow glacial lakes and wet hollows, peat accumulating on silt deposits (Rodwell, 1991). *Sphagnum* grows upwards, building peat until the surface vegetation no longer reaches groundwater; it is now ombrotrophic - fed entirely by precipitation. This creates infertile, acidic conditions. Raised bogs are dome-shaped due to *Sphagnum* growth (Natural England, 2020).

Undamaged bogs have two layers: an ‘acrotelm’ (a layer of living plants, mostly *Sphagnum*, and proto-peat) near the surface, and a lower ‘catotelm’. Compared to the catotelm, it has a lower bulk density (mass per volume) with larger pores, so higher water storage capacity, which provides drought protection. The underlying catotelm is permanently waterlogged and forms the bulk of the peat (Money & Wheeler, 1999). Decomposition here is very slow due to the lack of oxygen, and the active accumulation of peat is only possible with a living acrotelm (Bain *et al.*, 2011).

Most UK peatland research focuses on upland blanket bogs, with insufficient research on lowland bogs (Haddaway *et al.*, 2014). Lowland bogs (fens and raised bogs) comprise <10% of UK peatlands (Worrall *et al.*, 2011), however have higher land-use pressures than upland peat.

2.1.2 M18 *Erica tetralix-Sphagnum papillosum* raised mire

The National Vegetation Classification (NVC) describes plant communities in the UK, categorising them based on species assemblage. The restoration target for the sites is M18: the most characteristic raised bog type (JNCC, 2004). Rodwell (1991) describes M18 as lowland bog communities dominated by *Sphagna*, with ericoid sub-shrubs and monotyledons (grasses) playing a subordinate role. Plants that define this community are *Calluna vulgaris*, *Erica tetralix*, *Eriophorum* spp., the peat-building mosses *Sphagnum capilliforum, S. papillosum,* and *S. tenellum.*

Vascular plants are scattered through a *Sphagnum* carpet. A healthy bog has *Sphagnum*-rich hummocks and hollows, these variations in surface topography supporting diverse species adapted to soil moisture variations (Bain *et al.*, 2011).

This community occurs on waterlogged ombrogenous peats, with water supplied solely through precipitation. They receive 800-1200 mm precipitation year^{-1}, with 140-180 wet days year^{-1} (Rodwell, 1991). Run-off is reduced because M18 mires barely slope. Zonation is related to water-table height, horizontal water flow and the degree of water stagnation. Towards drier areas like well-drained margins, there is a transition to wet heath and then *Molinia*.

2.2 Peatland degradation

2.2.1 Historical damage

Many lowland peatlands have been drained for agricultural use, which oxidises peat and accelerates decomposition, releasing stored carbon back into the atmosphere. This causes peatlands to become carbon sources, increasing the greenhouse effect (Bain *et al.*, 2011). ~94% of lowland raised bogs in Britain have been damaged and destroyed through drainage and extracting peat for horticultural usage (Moore, 2002).

Wetland draining alters floristic composition from M18 *Erica-Sphagnum*, increasing the dominance of *Molinia* and *Calluna*. This starts at the edges, confining the community to the mire's centre (Rodwell, 1991). Sometimes the community becomes dominated by grasses like *Molinia caerulea*.

All sites had peat extracted using the cutover method (Thomas, 2015), where it is cut to a depth of 1-2 metres and dried out in piles, with the surface levels sometimes replaced on the bog (ManitobaPeatlands, 2012). This results in water table instability by exposing the dense catotelm, which has lower water storage capacity than the acrotelm. The catotelm may also be deficient in recycled nutrients (Money & Wheeler, 1999).

Damage like peat extraction removes the surface of the bog (the acrotelm) which has active peat-building vegetation like *Sphagnum*. 'Degraded' bogs may have some typical vegetation remaining, but lose their peat forming ability, while 'active' bogs support peat formation (JNCC, 2004).

2.2.2 *Molinia caerulea*

Purple Moor-grass (*Molinia caerulea*) is a tussock-forming grass that spreads rapidly in drier peatlands. Although *Molinia* is expected in low abundance in bog communities, especially on the drier margins (JNCC, 2004), sometimes it covers large areas, leaving little space for other species (Meade, 2015). Active raised bog should have grasses, dwarf shrubs and bryophytes (mostly *Sphagnum*) without one group dominating (JNCC, 2004), but *Molinia* domination reduces diversity.

Molinia abundance peaks on highly acidic soils (pH <4) and calcareous soils (pH>7). It thrives in well aerated, relatively high nutrient soil with ground-water movement (Taylor *et al.*, 2001). With 48% above ground biomass as leaves, it photosynthesises efficiently and increases biomass with increased nutrient availability (Anderson, 2015). Tussock height is not necessarily related to plant age, rather to water level (Underdown & Meade, 2015).

Molinia is an engineer species, creating conditions favourable for its growth (Gogo *et al.*, 2011). It reduces the growth of *Sphagnum*, shallow-rooting ericaceous species and cotton-grasses by drying out soil: its long roots gain access to deep water, and its high evapo-transpiration loses water to the atmosphere (Schouwenaars, 1990). It increases peat bulk density, resulting in lower water storage capacity (Gogo *et al.*, 2011).

Raised bogs are rain-fed, so are nutrient poor, supporting species adapted to acidic conditions (JNCC, 2004). *Molinia* increases carbon and nutrient levels. Vascular plants decompose faster due to high nutrient content, and input carbon into deep peat, increasing microbial activity and decomposition rates. This causes higher soil nutrient concentrations through nutrient recycling (Gogo *et al.*, 2011). This contrasts with the sphagnan chemicals and cell structure of *Sphagnum*, which immobilize nutrients, preserving organic matter (Gogo *et al.*, 2011). *Molinia* releases more carbon and nutrients into peat through its roots than wetland species like *Erica tetralix*, causing positive feedback as it grows more with the increased nutrient input, out-competing oligotrophic wetland plants (Aerts *et al.*, 1989).

Molinia dominance can be "symptomatic of a breakdown in ecosystem processes" (Stone, 2015, 71). Its impact on soil biochemistry has wider implications, and can directly increase wetland greenhouse gas emissions. *Molinia* slows new peat formation, decreasing CO_2 capture, and its extensive root system increases the mineralisation of deep stored organic carbon to CO_2, especially in drier, aerobic conditions (Gogo *et al.*, 2011).

Because *Molinia* enriches and dries peat, it can be a factor in succession from wet-mire to shrub-dominated vegetation communities (JNCC, 2004; Large, 2001). This is undesirable as it decreases the size of the raised bog (JNCC, 2004) by encroaching in drier areas and creating conditions more suitable for the growth of other vascular plants, rather than raised bog species like *Sphagnum*. Peat damaged by peat cutting is more suitable for *Molinia* growth than species like *Sphagnum*. To restore healthy, wet, nutrient-poor raised bog, *Molinia* that dries and enriches peat should be reduced.

However, there are some controversies about *Molinia*'s role on peatlands. Jepson (2015) argues that *Molinia* provides suitable microclimates for *Sphagnum* growth, and under waterlogged, anoxic conditions, decomposition is slowed enough that *Molinia* litter forms peat. This highlights the need for further *Molinia* research.

2.3 Management

2.3.1 Restoration goals

The broad aim of peatland restoration is to re-establish active peat formation by supporting vegetation communities that build peat (Lunt *et al.*, 2010). *Sphagnum* and cotton grass (*Eriophorum* spp.) are the main peat-forming species in UK raised bogs (JNCC, 2004). The Joint Nature Conservation Committee has targets described in Common Standards Monitoring Guidance to help assess lowland wetland condition (ibid.).

Vegetation composition is monitored, as different plants indicate bog condition. Specific species are positive or negative indicators for raised bog, so targets are based around their frequency and cover. Frequency describes how often a species appears in different samples (Rodwell, 2006): 1-20% rare, 21-40% occasional, 41-60% frequent, >60% constant.

Positive indicators:

- At least three species should be constant but not >80% cover: *Calluna vulgaris, Erica tetralix, Eriophorum angustifolium, E. vaginatum and Trichophorum cespitosum.*
- No one vascular plant species should have >50% cover.
- At least one specialised bog species like round-leaved sundew frequent.
- *Sphagnum cuspidatum* at least occasional.
- >20% combined cover of at least two of these *Sphagnum* species: *S. capillifolium, S. magellanicum, S. papillosum, S. tenellum.*
- A mix of mostly *Sphagnum*, graminoids and dwarf shrubs without any group dominating.

Some non-woody vascular species, like bracken, are indicators of negative change (enrichment and drying out of the bog), so should not cover >1%. *Molinia* is not specifically mentioned as a negative indicator, however is more abundant on degraded sites. Frequent *Polytrichum* moss, and tree cover, are also indicators of negative change (JNCC, 2004).

2.3.2 Management techniques

Managing areas with the aim of a raised bog community requires consideration of hydrology, nutrients and the control of invasive species. There must be sufficient supply and retention of precipitation water; damaged bogs frequently have unstable water tables. A drop to 50-100 cm subsurface, common in summer, is too dry for *Sphagnum* establishment (Money & Wheeler, 1999). Thus, raising and maintaining the water table is central to bog restoration, as it allows characteristic plants and structural features (e.g. bog pools) to re-establish (JNCC, 2004). Historic drainage is blocked off and bunds (barriers made by compacting peat) constructed, sometimes with supportive piling, to keep water on site (Thomas, 2015). Internal bunds prevent flow within the peat, surface bunds prevent surface flow, and trench bunds combine the two (Mainprize, 2022).

Vascular plants, especially large trees, are cut to reduce evapotranspiration water losses (Schouwenaars, 1990). The site can be flooded, with open water enabling growth of floating *Sphagnum* mats, however lagoons must be kept small to prevent wave action from impeding *Sphagnum* growth (Money & Wheeler, 1999).

2.3.3 Weakening *Molinia*

In order to reduce *Molinia*'s negative impact on raised mires, various management strategies are applied to weaken it and reduce its frequency, abundance and size. Herbicides like propaquizafop can reduce growth, however require follow-up applications to prevent regrowth (Marrs *et al.*, 2015). Intensive grazing has been used to prevent regrowth in combination with methods like cutting (Perry, 2015). *Molinia* spreads fast after wildfire (Jacquemyn *et al.*, 2005), so fire is not effective.

Because *Molinia* prefers drier soils than mire vegetation, inundation can weaken it. Plants exude oxygen from roots to survive anaerobic conditions, however this mechanism is lower for *Molinia* than for Common cotton-grass. Stagnant water especially reduces its productivity. Waterlogged soils have slower decomposition, and *Molinia* is less adapted to resulting lower nutrient levels than plants like *Erica tetralix* (Anderson, 2015).

'Flailing' (mowing all vegetation to <1cm using blades attached to a rotating drum (CGM, n.d.)), reduces *Molinia* dominance. It can increase bare ground and species diversity (Rosenburgh, 2015), reduce *Molinia* cover, height and tussocky structure, including over several years (Marrs *et al.*, 2015; Daggett, 2015). A farmer in Trumau reported it taking ~6 years for it to recover with significant biomass to warrant another cut (Perry, 2015). It smashes up tussocks, reducing nutrient stores in the roots and basal internodes (Taylor *et al.*, 2001), and leaving a good seed bed for other species to establish. Gaps in the canopy enable *Sphagnum* to reach the peat substrate better (Rosenburgh, 2015). Flailing can raise mean water table levels (Pilkington, 2015). Cutting multiple times proves most effective at reducing *Molinia* cover (Marrs *et al.*, 2015).

Cut-up plant material can either be removed from the site, or left on the surface as mulch (Figure 1). It is chopped finely so decomposes rapidly and does not prevent other species growing(Perry, 2015). Mulch can protect bare peat, as in Y Gyrn where mulch spread at 5-15 cm depth provided a physical protective barrier against wind and water erosion and peat oxidation, enabling vegetation growth (Daggett, 2015). It can suppress woody plant growth and is more affordable than removing plant material (Bódis *et al.*, 2021).

Figure 1: Mulching on Astley (LWT, 2023).

However, *Molinia* is N-limited (Taylor *et al.*, 2001), so benefits from nutrients released by decomposing mulch (Meade, 2015). Mulch may be more effective for bog restoration in wetter locations (Money & Wheeler, 1999).

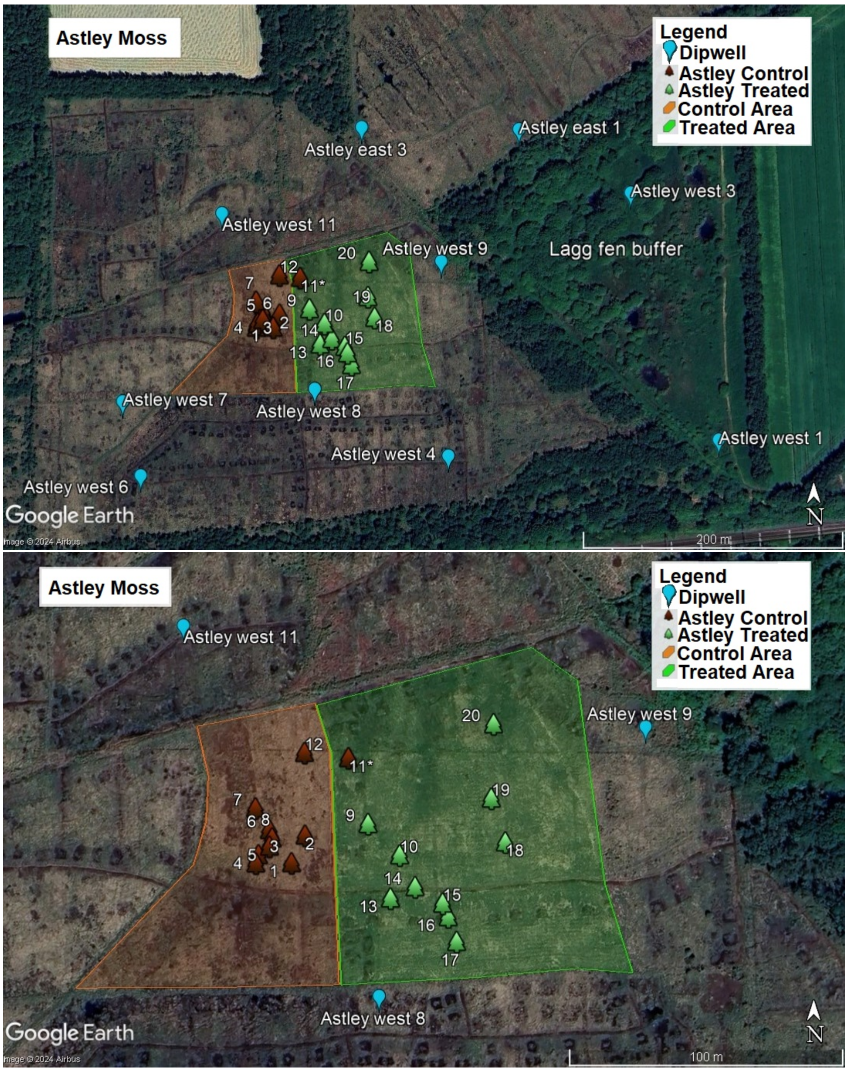
Reduced abundance of *Molinia*, and weaker, less tussocky growth enables it to be less competitive and more able to mix with other plants (Anderson, 2015). This study is important, as research is lacking on the effects of mulching, especially on lowland bogs, which differ from upland peat in hydrology, topography, usage and structure so may be impacted by *Molinia* differently. Management options differ as lowland peat is flatter, making it easier to block drainage and contain water onsite (Meade, 2015).

2.4 Study Area and Aims

2.4.1 Location

Three sites will be compared:

- Astley Moss Control (AC); non-mulched area 53°28'17.86"N 2°27'40.73"W
- Astley Moss Treated (AT); mulched area 53°28'18.18"N 2°27'36.70"W
- Rindle Moss Treated (RT); mulched 53°27'53.10"N 2°26'54.33"W



(a) Astley Moss. Top shows wider area and lagg fen buffer; lower map zoomed to study area.

(b) Rindle Moss study area.

Figure 2: Study site maps (Google Earth, 2023), showing shaded study areas, numbered vegetation quadrats, and dipwells.

2.4.2 History of Chat Moss

Astley and Rindle Moss are part of Manchester Mosses Special Area of Conservation (SAC), consisting of 3 relict bog sites. These are the largest remaining fragments of Chat Moss, a peatland historically covering large areas of the Mersey Valley. The Manchester Mosses are lowland raised bog at 21 m elevation. They first developed within discrete basins, then blanketed the landscape in bog, with rapid expansion between 5000 and 1000 BCE. In 1830, railway access resulted in conversion to agriculture and large scale peat cutting. Much of the bog was lost, with remaining fragments only part of the wider paludified landscape (Thomas, 2015).

2.4.3 Astley Moss

Figure 3: Photo of Astley Moss West (subsequent photos author's own).

Prior to Lancashire Wildlife Trust (LWT) acquiring Astley Moss in the mid-1980s, it was drained and used for peat cutting for decades under British Coal ownership. Adjacent land was drained for agriculture (J. Lawson, 2024, pers. comm., 14 March).

In the early 1990s, the LWT blocked internal drainage ditches to raise water levels, creating suitable conditions on the peat cuttings for a bog community (Thomas, 2015). *Molinia* encroachment has long been a problem (Natural England, 1989) as the fluctuating water table dries peat. *Betula pubescens* also began growing, though was removed in 2006 (Wigan Council, n.d.).

An agricultural field north of the site prevented full ditch blocking; as these were up to 3m deep, water seeped out. Also, ground level differences caused water to escape from higher areas (old peat cuttings) due to the hydrological gradient.

Since 2000, plastic piling has been installed to isolate the site from external drainage. Piling was driven into the underlying clay, with bunds built over it (Thomas, 2015). Peat was dug from "borrow pools" to construct bunds, simultaneously slowing water flow offsite and retaining standing water on the peat surface. Several large bunds were constructed between 2006 and 2013, and smaller bunds in 2021-2022.

A lagg fen buffer was created east of the site in 2009. Previously a carrot field, it was too nutrient-rich to be a bog; however, bunding, blocking drains, and digging pools raised the water table, giving the site protection from external drainage (J. Lawson, 2024, pers. comm., 14 March).

Astley Moss (West) is ~9.5 hectares and *Molinia* dominates part of the site. 1.1 ha was mulched in Winter 2022/23; this makes up the Astley Treated site (AT), while a part that was not mulched (0.58 ha) until October 2023 is the control (AC) (Figure 2a). Mixed *Sphagnum* plugs were planted on the mulched area between 2020-2023, and *Eriophorum vaginatum, E. angustifolium* and *Erica tetralix* on adjacent sites (ibid.).

2.4.4 Rindle Moss

Rindle Moss is a 5 ha site located next to Rindle Farm paludiculture trial. Details of its history are unclear, however before the 21st century it was drained and cut for peat, with shallow ditches crossing the bog. Long plastic pipes were used for drainage, with the intention of agricultural usage, however this did not occur (J. Lawson, 2024, pers. comm., 14 March). Afterwards, it was used for walks and quad biking, forming ruts that supported some *Sphagnum* (Keightley & Rogers, 2021).

Some healthy *Sphagnum* patches remained when LWT gained ownership in 2021, with a mean cover of 14.93%. *Molinia caerulea* dominated the vascular vegetation, and birches were growing (ibid.). Water table management to flood *Molinia* out was carried out in Winter 2022/23. Trees were cut down as they absorb water, with woodchip used to infill a deep drainage ditch to the north of the site. The rest was scattered on parts of the site; a thin layer may help *Sphagnum* grow, suppressing weeds and protecting bare peat from solar radiation (J. Lawson, 2024, pers. comm., 14 March). Woodchip can slow decomposition through the release of phenolic compounds that suppress enzyme

Figure 4: Photograph of Rindle Moss.

activity, reducing CO_2 output to the atmosphere (Alshehri *et al.*, 2020). The site was was mulched in January 2023. *Sphagnum* plugs were planted March 2023 (J. Lawson, 2024, pers. comm., 14 March). *Eriophorum vaginatum* was planted in September 2023, though already grew in some areas. The water table is noticeably higher than at Astley, with large parts inundated; this occurred after a prolonged drought in Spring 2023 and subsequent rain.

2.4.5 Study aim

This study aims to explore whether mulching vegetation in *Molinia*-dominated lowland peatland improves restoration to a diverse raised bog community. Vegetation composition will be compared between mulched and non-mulched sites to assess whether *Molinia* is weakened and key mire vegetation like *Sphagnum* is more abundant.

Interactions between water table and vegetation will be explored. Rindle has a more isolated water table than Astley, so comparing Astley and Rindle will demonstrate water table impact on vegetation. Comparing vegetation between Astley Control and Treated will show the impact of mulching, as the hydrology is broadly similar. At Rindle, interactions between plants and peat conditions will be assessed to explore mechanisms for vegetation changes.

2.4.6 Research questions

1. Are there differences in the vegetation communities present at each site?
2. Is there a relationship between water table, soil moisture and abundance of wetland vegetation and *Molinia*?
3. Are there relationships between peat conditions and vegetation at Rindle Moss?
4. Does mulching *Molinia* bring the vegetation community closer to the restoration goal (M18: *Erica tetralix-Sphagnum papillosum* raised mire)?

2.4.7 Hypotheses

1. Treated (mulched) sites will have different vegetation composition to the control site, with lower *Molinia* dominance and higher abundance of wetland vegetation like *Sphagnum*, as shown in previous studies like (Rosenburgh, 2015).
2. Higher water table and soil moisture will correlate with increased abundance of *Sphagnum* as it requires wet conditions (Price & Whitehead, 2001), and lower *Molinia* as it prefers aerated substrates (Taylor *et al.*, 2001).
3. Vegetation and peat characteristics are closely linked in peatlands (Andersen *et al.*, 2011). Higher *Molinia* is expected to increase bulk density (Gogo *et al.*, 2011). Higher nutrients like N are expected to correlate with higher *Molinia* (Anderson, 2015) and lower *Sphagnum* (Aerts *et al.*, 1999). Results will be explored for other possible relationships (Steel *et al.*, 2013).
4. Mulching *Molinia* brings the vegetation community closer to the M18 restoration goal. Treated sites are expected to have NVC classifications more similar to M18 than the control, as flailing can increase characteristic peat-forming plants like *Sphagnum* (Rosenburgh, 2015).

3 Methodology

3.1 Data collection

Primary data was collected in September 2023. All sites were surveyed for vegetation, including preliminary studies to assess safety and practice plant identification and cover estimation. Astley is a SSSI and requires application to take samples, so peat samples were only collected at Rindle. Site access and sample collection permissions were granted by the LWT.

3.1.1 Vegetation

Surveys based on NVC were carried out to ascertain vegetation diversity, abundance and frequency. Ten 1 m^2 quadrats were assessed for each site. Rodwell (2006) recommends 2 m^2 for herbaceous vegetation and dwarf-shrub heaths, however this was too large to effectively assess. Pragmatic sampling was used to select homogenous, representative stands avoiding ecotones. I first walked over sites to understand the pattern of variation and look for uniformity of vegetation colour and texture (ibid.). A small quadrat was thrown to randomise quadrat location, reducing bias towards diverse patches.

Plants were identified to lowest taxonomic level. Percentage cover by species and ground type (e.g. bare peat) was estimated. This is a linear scale, so analysis is simpler (Currall, 1987), with more information maintained than for non-linear scales like Domin (Birnie *et al.*, 2005). Within-quadrat percentages exceed 100% when plants overlap. Plants with <1% cover were converted to 0.5% for data analysis. Vegetation height was measured at quadrat corners by layer: small tree, field (mostly *Molinia*), and ground (mostly mosses).

Sampling cards were adapted from Rodwell (2006) to document additional data (Appendix A.1). Locations were obtained using a smartphone app (Surveyor.DEV, 2022) with an accuracy of ~7 m. Photographs and field sketches provide supplementary information, like species not present in quadrats.

3.1.2 Peat characteristics

Peat was sampled at Rindle from as near to each vegetation quadrat as possible using photos and a GNSS receiver to locate the same area. Bulk density was sampled using a 104.62 cm^3 metal ring. Peat samples were taken using a trowel and by hand from the top 20 cm of the peat. This is within the plant rooting depth recommended for chemical composition analysis (Osborne & DeLaune, 2013); *Molinia* can root beyond 80 cm depth (Taylor *et al.*, 2001). 71% of sampling points were submerged. Two general and two bulk density samples were taken for each quadrat. Samples were stored in the cold room and weighed to four decimal places for grams, and three for milligrams. UoM Geography Lab Standard Operating Procedures were followed for sample preparation.

3.1.3.1 Hydrology: water table and soil moisture

The LWT provided water table data. Most representative dipwells closest to survey sites were selected using Google Earth (Google Earth, 2023). Both Astley sites used the same dipwells due to coarse resolution. Rindle dipwell 6, although near quadrat 25, was excluded from comparison due to unrepresentatively low water table (Appendix A.3). Selected dipwells were aw8, aw9, r2, r4, r5 (Figure 2). Rindle data from before bund construction in February 2023 was removed.

To measure soil moisture, ~3g of each peat sample was measured into porcelain crucibles. Wet weight was measured. These were dried in a furnace at 105°C, then weighed to calculate dry weight.

3.1.3.2 Organic matter

These samples were put in a Carbolite Gero AAF 1100 furnace at 550°C for 2 hours to burn off organic material. They were weighed to calculate soil organic matter (SOM) (Berglund, 1987).

3.1.3.3 Bulk density

Bulk density samples were weighed before and after drying in an oven at 105°C in foil trays.

3.1.3.4 Nutrients

Peat samples 100-150 grams were frozen at -20°C, then dried in a freeze-dryer (Christ Alpha 1-4 LSCplus). They were homogenised, then sieved at 0.5 mm and ~5 g weighed samples diluted with 50 ml of ultrapure deionised water. They were centrifuged at 4500 rpm for 5 minutes after a 30 minute ultrasonic bath. 10 ml of each sample was filtered through a 0.45 µm Whatman filter in 13.5 ml tubes. These were analysed in a Metrohm 882 Ion Chromatography machine for fluoride, chloride, bromide, nitrate, phosphate and sulfate, with a 0.05 µg/L limit of detection. This method is based on ISO 20702:2017 (2018). Results were mass corrected with the equation $x = (d * n)/mass$ where d is the dilution factor (50ml) and n is the raw result.

Freeze-dried, homogenised samples weighing ~2 mg were analysed using a CHSN/O Organic Elemental Analyser (Thermo Scientific Flash 2000) for nitrogen, fluoride, hydrogen, sulphur and total carbon (organic and inorganic). It uses 5 point calibration with a 0.999% correlation coefficient; results are based on an average of three replicates for each sample. This method is based on ISO 15936:2022 (2022).

3.1.3.5 pH

Remaining solution from 3.1.3.4 was measured for pH based on BS-EN 15933-2012 (2012) methods using a Mettler Toledo SevenCompact probe calibrated with a 4-point calibration at pH 2.0, 4.0, 7.0, and 9.0.

3.2 Data analysis

Graphical and statistical analysis and presentation was carried out using Excel (Microsoft, 2018) and R (RCoreTeam, 2018) with packages ggplot2 (Wickham, 2016) tidyverse (Wickham *et al.*, 2019), vegan (Oksanen *et al.*, 2022), dplyr (Wickham *et al.*, 2023), viridis (Garnier *et al.*, 2024), gridExtra (Auguie, 2017), reshape2 (Wickham, 2007), pastecs (Grosjean & Ibanez, 2024) and twinspan (Oksanen & Hill, 2019). P-values <0.05 were considered statistically significant. Shapiro–Wilk tests checked normality of distributions, where $P>0.05$ was considered normal, to ensure appropriate statistical tests and plots. Kruskal-Wallis tests were used for non-parametric data comparison (Gardener, 2014), and ANOVA when it was normally distributed.

3.2.1 Vegetation comparison

3.2.1.1 Biodiversity

Kruskal-Wallis tests compared differences between sites in percentage cover of key vegetation, species richness (number of species) and Simpson's Diversity Index (SDI) within quadrats. SDI was calculated for each quadrat using the equation:

$$SDI = 1 - \frac{\sum n(n-1)}{N(N-1)}$$

where n=percent cover of one species within the quadrat, and N=the total percent cover of all species in that quadrat (Kelly, 2020). SDI by site was calculated with the `diversity` function in R package vegan, using this equation:

$$SDI = 1 - \sum p_i^2$$

where p_i is the proportional abundance of species i (Oksanen *et al.*, 2022), using total percentage cover of each species within each site.

3.2.1.2 TWINSPAN

Two-way indicator species analysis (TWINSPAN) clustered vegetation quadrats by similarity to compare sites (Hill & Hill, 1979). Quadrats are divided based on how different they are to others, based on pseudospecies defined by percentage cover abundance

(Peeters & Gylstra, 1997). Cut levels were 0,1,5,10,20,40,60, as the default was insensitive to cover above 20%, and cover varied above 20% (Appendix A.2).

3.2.1.3 Vegetation height

Because *Molinia* is smaller when it is weaker (Daggett, 2015), average field layer height was compared between sites using ANOVA.

3.2.2 Hydrology

3.2.2.1 Water table

Difference between Astley and Rindle water tables was compared with the Wilcoxon-signed-rank test, for two groups of non-parametric data (Wilcoxon, 1945). Impact on vegetation was inferred, as data was too course for quadrat-scale correlation.

3.2.2.2 Soil moisture

At Rindle, correlations between mean soil moisture and key vegetation cover (*Molinia, Sphagnum*) were tested. Interactions may show relationships between peat moisture and plant abundance, and help interpret water table impact across sites.

3.2.3 Peat characteristics

A correlation matrix (Appendix A.5) was carried out to visualise possible relationships between mean peat characteristics (nutrients, bulk density and pH) and key vegetation cover (Steel *et al.*, 2013). Vegetation trends were explored, and for linear trends, R^2, p-value and effect size are reported. Non-linear relationships were fitted using MyCurveFit (n.d.), which did not provide p-value or effect size, so only R^2 is reported for curves. Quadrat rt5/25 was different to other parts of Rindle; it was from the dry central strip, which had no *Molinia*, mostly bracken. Nitrate was ~27 mg/L higher than at other quadrats, skewing results, so was removed to better visualise relationships between *Molinia* and nitrate (Steel *et al.*, 2013).

3.2.4 National Vegetation Classification

The closest NVC community classifications were calculated using MAVIS software, based on frequency of species between quadrats (Smart, 2016). It matches sites to communities described in Rodwell (1991) and does not consider abundance.

4 Results

4.1 Vegetation composition

Figure 5 shows the results of the vegetation surveys. *Molinia caerulea* is highest at Astley Control (AC), decreasing at Astley Treated (AT) and Rindle Treated (RT). There is *Calluna vulgaris* at all three sites, slightly higher at AC. *Pteridium aquilinum* makes up just over 13% of RT, but is negligible at AT and not present at AC. *Sphagnum cuspidatum* makes up over 25% of vegetation proportion at RT, but is not present at Astley. There is a high proportion of *Hypnum jutlandicum* at AT compared to the other two sites. *Polytrichum commune* is present at all sites, slightly more abundant at AT.

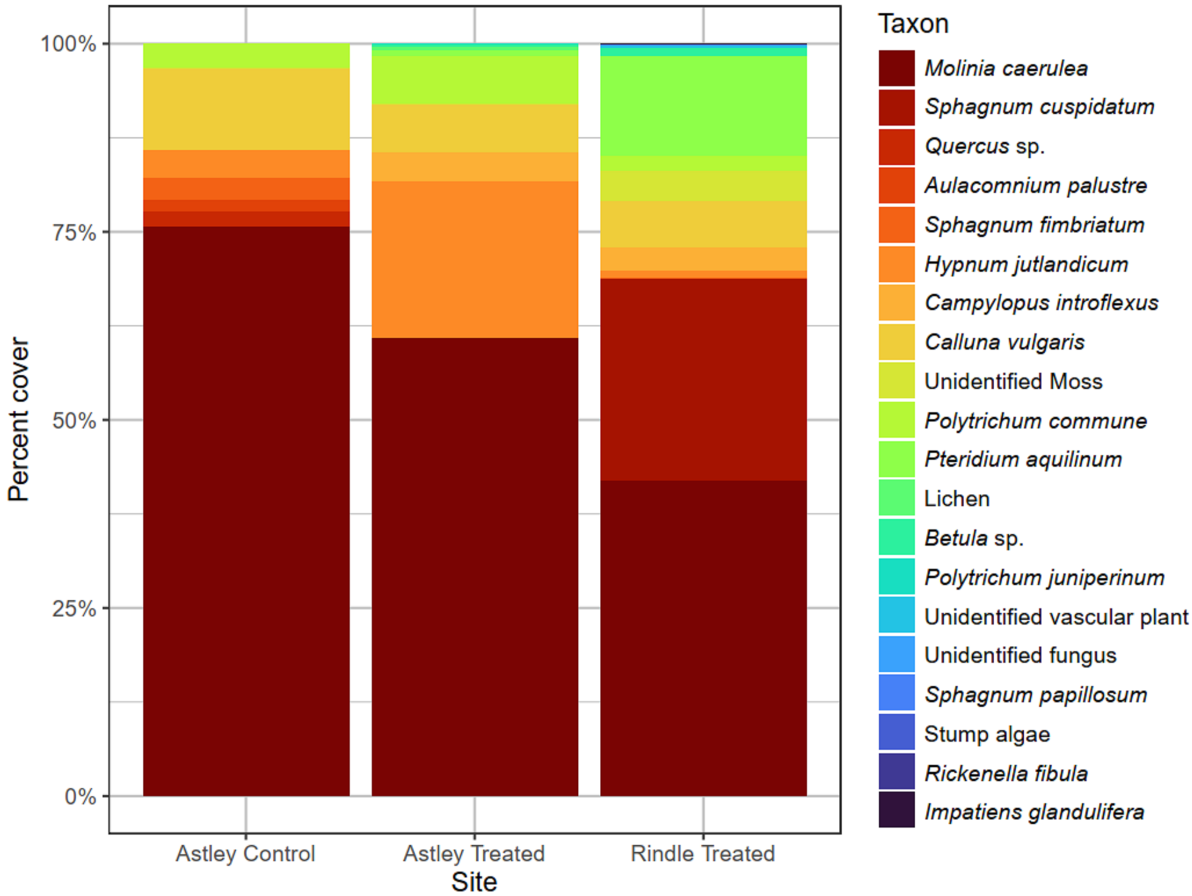


Figure 5: Mean vegetation percent cover proportion by site and taxon, normalised to 100%.

Live biomass was highest at the control due to the large area *Molinia* covers when it grows tussocky, 'dead plant' highest due to dry *Molinia* litter. Rindle was the only site with quadrats in submerged areas, reflected in the bog pool measure (Figure 6). AT had less biomass and no bog pool, so the highest bare ground. Rindle had *Betula* woodchip in several areas.

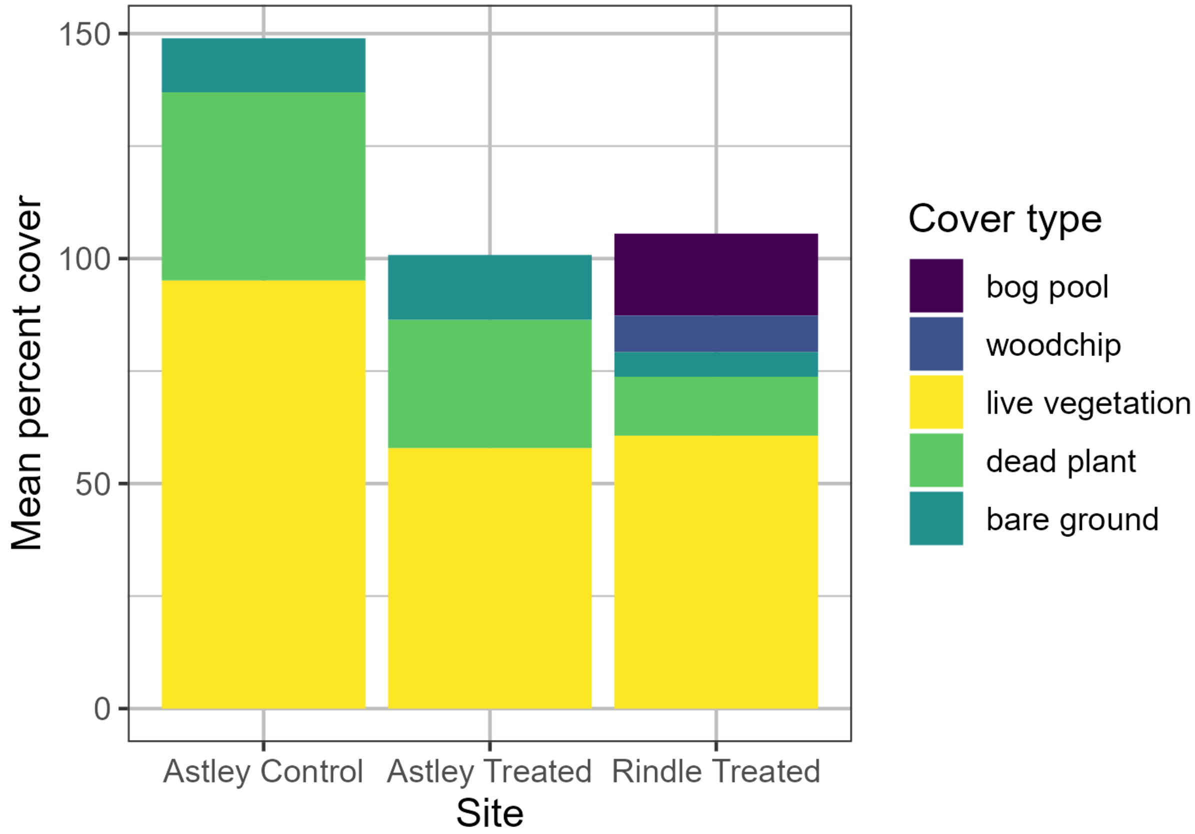


Figure 6: Total mean cover type percentage by site.

Reducing *Molinia caerulea* and increasing *Sphagnum* is a goal of the treatment, so percentage cover of key vegetation within quadrats was compared between sites (Figure 7). Kruskal-Wallis tests showed significant difference in percentage cover between sites for *Molinia* (χ^2=16.403, p=0.00027), *Sphagnum* (χ^2= 7.1309, p=0.02828), and non-*Sphagnum* mosses (χ^2= 7.1771, p=0.02764). There was no significant difference between *Calluna vulgaris* between sites (p=0.6275). Mean *Molinia* cover within quadrats was highest at AC (71.9%), followed by AT (35.2%) and RT (25.4%). No *Sphagnum* appeared in AT quadrats . RT had higher mean *Sphagnum*, present in more quadrats (16.9%, 5/10) than AC (2.7%, 2/10). Although difference was not significant, *Calluna* had higher percentage cover at AC (10.2%) than treated sites (AT=3.65%; RT=3.75%). Non-*Sphagnum* mosses were highest at AC (18.15%), lowest at RT (5.55%) and 8.3% at AC.

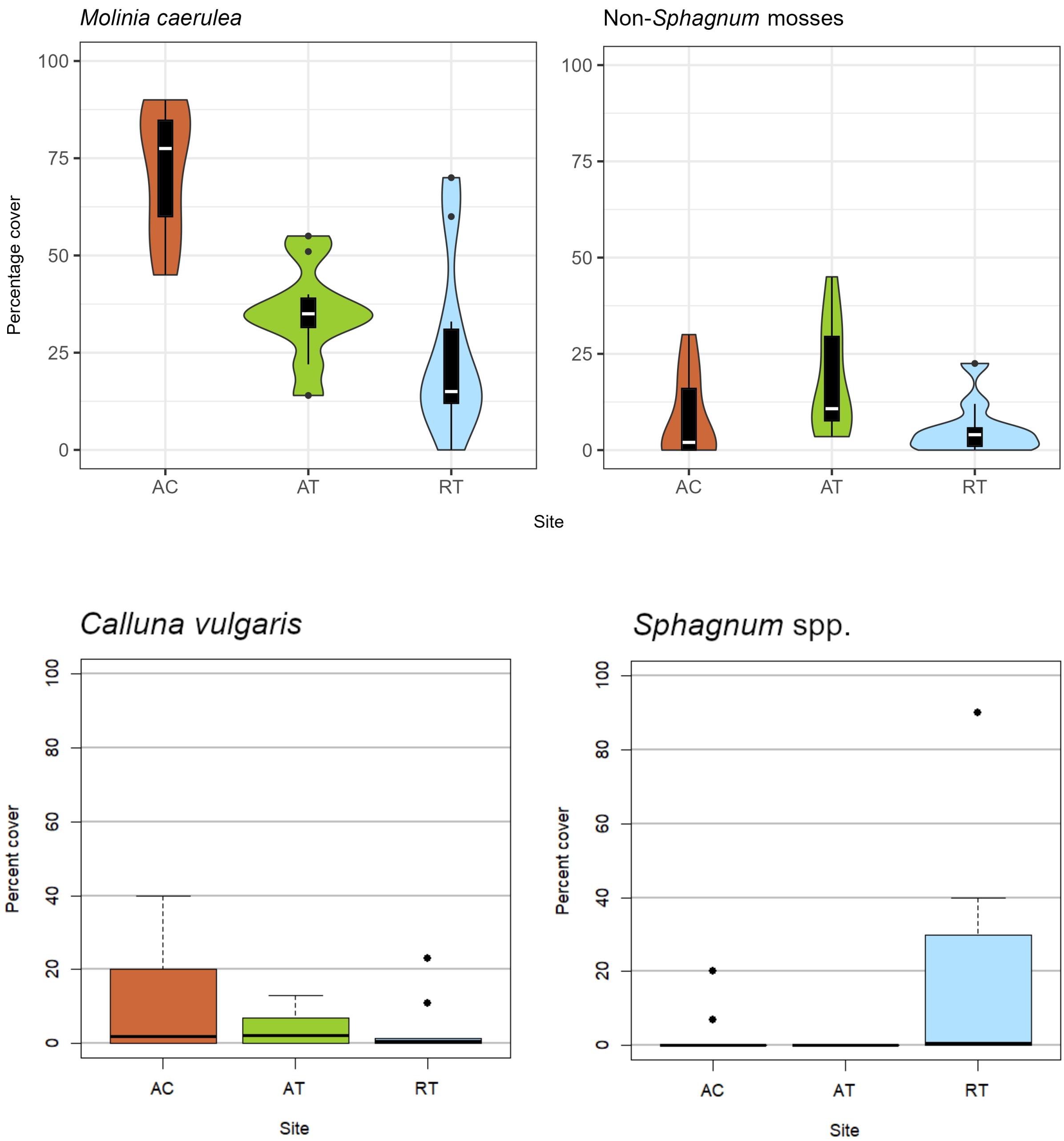


Figure 7: Distribution of percentage cover within quadrats of *Molinia caerulea*, non-*Sphagnum* mosses, *Calluna vulgaris* and *Sphagnum* spp. Violinplots show kernel density of percentage cover distribution.

4.2 Biodiversity

Total and mean species richness were slightly higher at treated sites (Table 1), however there was no significant difference in within-quadrat species richness between sites (Kruskal–Wallis χ^2=1.7642, p=0.4139). Species richness was normally distributed at AC (Shapiro–Wilk p=0.1583), but skewed higher for the treated sites (Figure 8).

Table 1: Total and mean species richness by site.

Site	**Species richness**	
	Total	**Mean**
AC	8	2.8
AT	9	3.7
RT	12	4.1

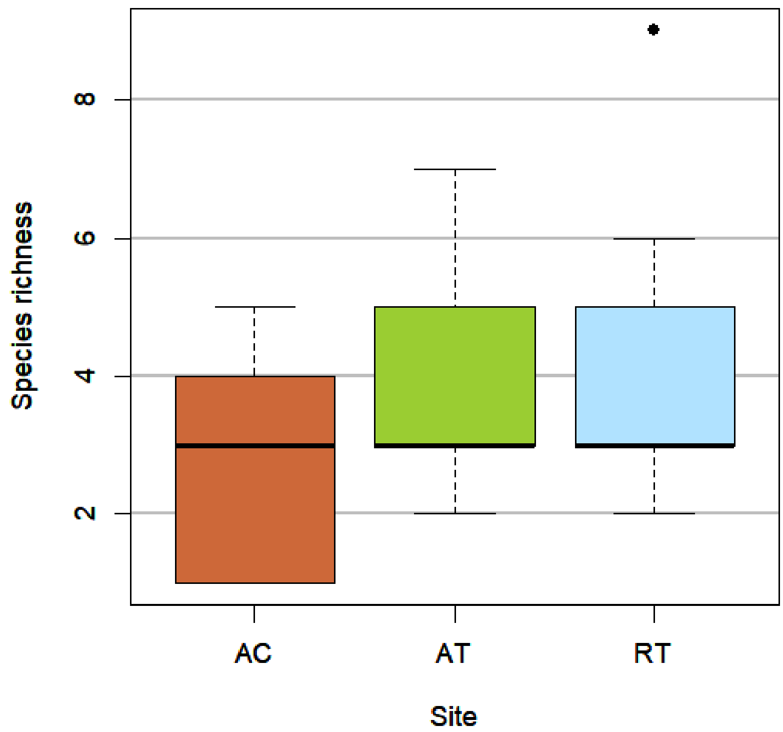


Figure 8: Species richness by quadrat compared between sites.

Figure 9 shows that Simpson's Diversity Index (SDI) within quadrats at AC ranges from 0, where there is only one species, to 0.64, while diversity is higher at RT and highest at AT. Median within-quadrat SDIs are AC=0.2438, AT=0.4839, RT=0.4359. However, there is no significant difference in within-quadrat SDI (Kruskal-Wallis χ^2=1.7383, p=0.4193). SDI was also calculated for each site. It was lowest at AC (0.4111), middling at AT (0.5764) and highest at RT (0.6329).

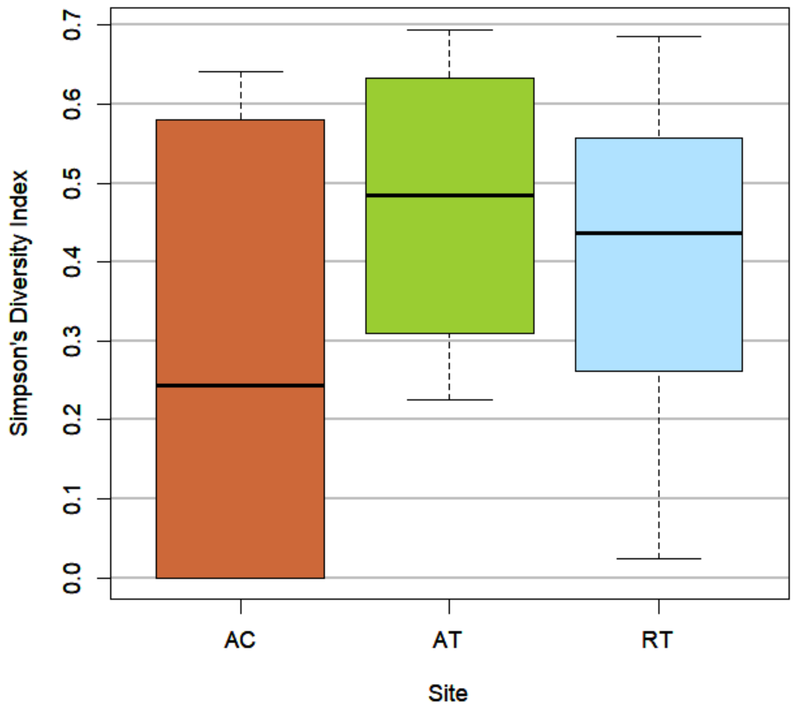


Figure 9: Simpson's Diversity Index (SDI) within quadrats compared between sites. SDI is the chance (1=100%) two randomly selected areas in a quadrat contain different species.

4.3 TWINSPAN clustering

TWINSPAN shows that vegetation composition generally differs greatly between AC and RT, while AT is in the centre of the continuum. Groups towards the right of Figure 10 were generally less *Molinia*-dominated. Groups I-K, consisting of treated quadrats mostly at Rindle, were characterised by *Betula* presence, and less *Molinia* >20% than groups A-H. *Sphagnum cuspidatum* >10% characterised group K, which contained three Rindle quadrats.

In contrast, groups A-H quadrats (N=21) had *Molinia* >20%; this included all Control quadrats, most AT quadrats and only two at Rindle. Absence of *Hypnum jutlandicum* divided most Control quadrats (N=8, groups A-C) from groups D-H. *Calluna vulgaris* above 5% characterises group C, while A and B are almost entirely devoid of plants except *Molinia* (Appendix A.7), demonstrating its dominance at AC.

Most Astley Treated quadrats are within subset D-H, however these groups contain quadrats from all sites. Groups G and H are all AT sites, representing quadrats with fairly low *Molinia* (median: 35%), some *Hypnum jutlandicum* and *Calluna*. Groups D-F are characterised by *Molinia* above 40% but have higher species richness than groups A-C.

Group F is unusual, grouping rt6 and rt9 with AC quadrats, likely due to higher *Molinia* and *Calluna* than other RT quadrats, similar to abundances at ac2.

Most Rindle quadrats were to the right of the dendrogram, characterised by *Betula* presence, and *Molinia* cover <20%. Almost all control quadrats were to the left, characterised by *Molinia* domination, low diversity and low *Hypnum jutlandicum*. Astley Control quadrats are most different to Rindle in their vegetation composition. Astley Treated quadrats have similar vegetation communities to other sites. They are grouped into those with low *Molinia* (G-H) and those with higher *Molinia* but that are more diverse than at Astley Control.

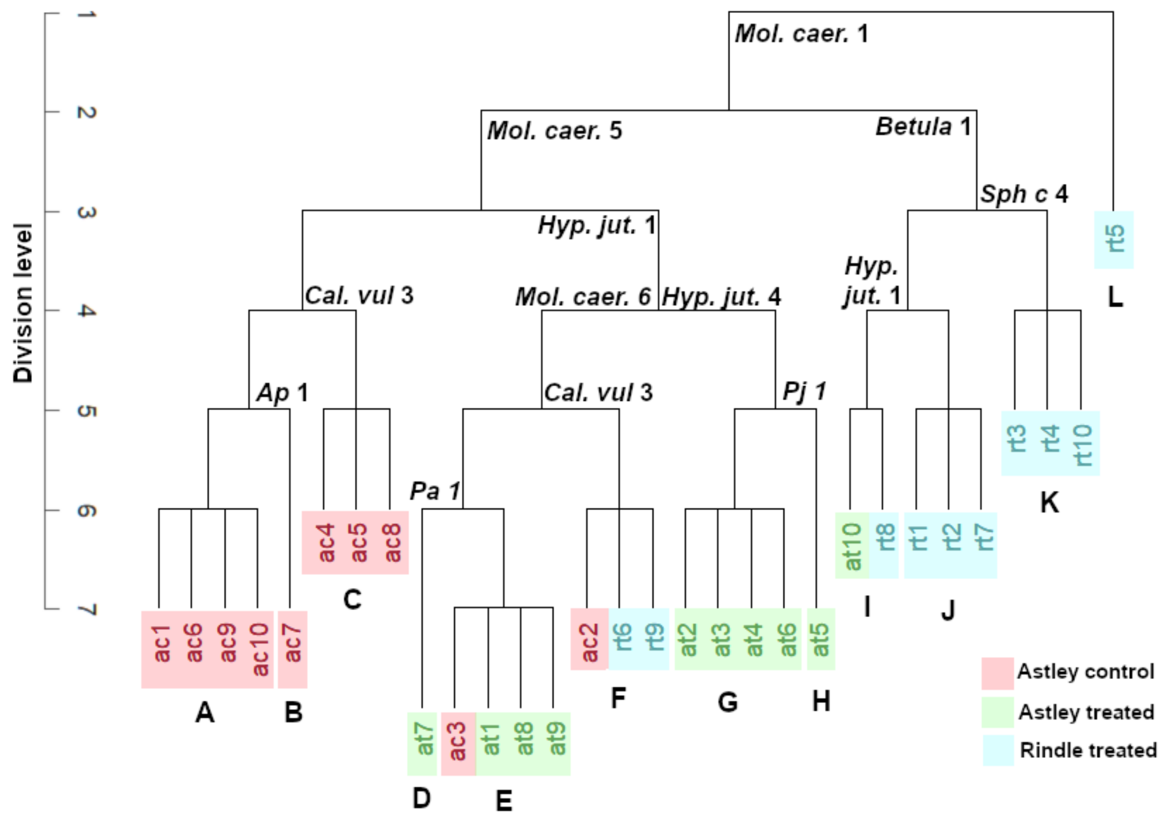


Figure 10: TWINSPAN-clustering; grouping quadrats through vegetation composition. Each vertical label (e.g. ac1) represents a quadrat; letters A-L show groups. Division levels are at the left. Indicator species used to select each division are on the branch leading to the group where it was more dominant. Numbers after indicator species represent pseudospecies abundance bands for that division. Indicator species abbreviations: *Mol. caer. = Molinia caerulea; Hyp. jut. = Hypnum jutlandicum; Sph c = Sphagnum cuspidatum; Cal. vul = Calluna vulgaris; Ap = Aulacomnium palustre; Pj = Polytrichum juniperinum; Pa = Pteridium aquilinum.*

4.4 Vegetation height

There was significant difference in field layer height between sites (ANOVA: F=4.749, p=0.0104). AC had taller field vegetation, at RT it was middling, and AT had the lowest

(Means (cm): AC=92.525, AT=67.9, RT=83.425).

Site had a significant impact on ground layer plant height (Kruskal Wallis χ^2= 21.967, p= 1.698 $\times$ 10$^-$5). Bryophytes were taller at AC, and shortest at AT (Means (mm): AC=99, AT=34.98, RT=42.88).

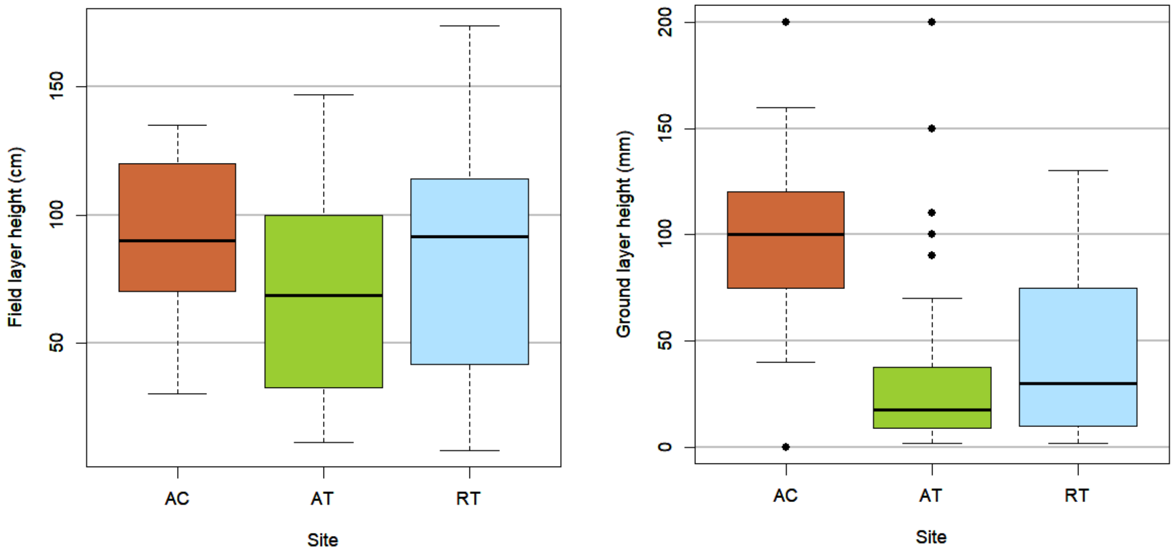


Figure 11: Field and ground layer height by site.

Most field-layer plants were *Molinia*, and because treated areas had lower *Molinia* percentage cover (Figure 7) and visually *Molinia* looked shorter and less tussocky, the correlation between *Molinia* abundance and field-layer plant height was tested. Linear regression showed significant positive correlation (β(cm)=0.2857, $R^2_{multiple}$=0.04057, t=2.234, df=118, p=0.0274).

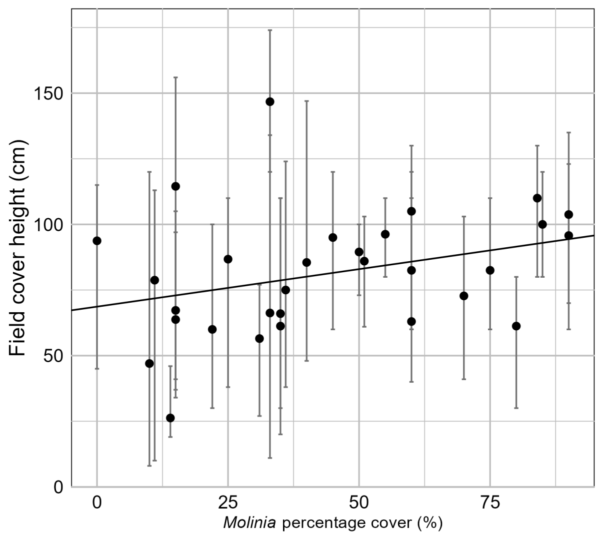


Figure 12: Function of *Molinia* percentage cover on height of field layer plants, showing linear trend.

4.5 Water Table

There was significant difference in water table depth between Astley and Rindle (Wilcoxon rank test: W=118.5, p=0.02933); water was closer to the surface at Rindle (Figure 13) and standing water was widespread (Figure 4).

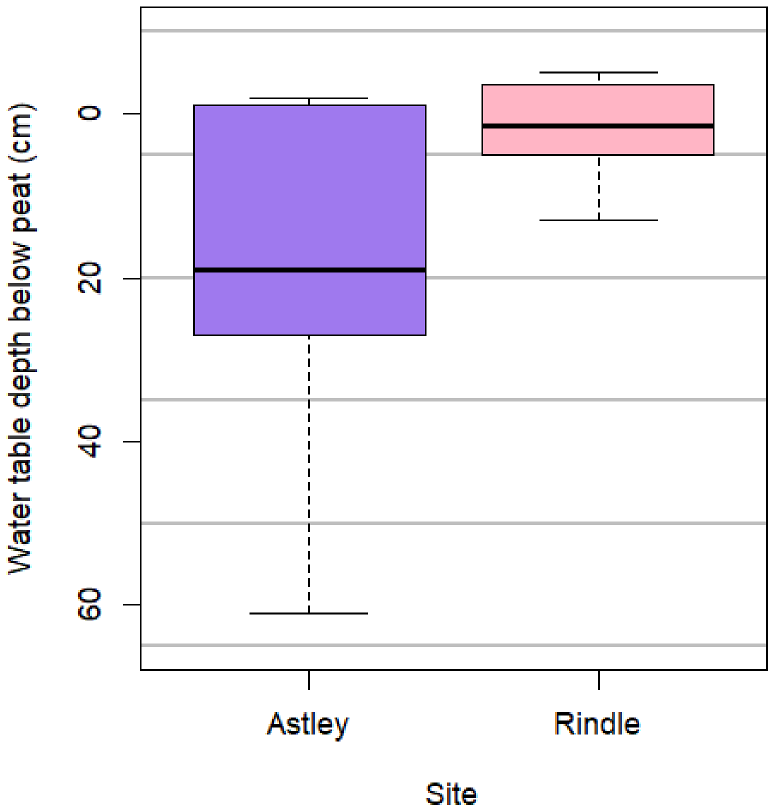


Figure 13: Dipwell depth ranges at Astley and Rindle.

Figure 14 shows water table changing between Autumn 2022 and 2023, overall getting closer to the surface before plateauing. Late Spring and Summer show a slight deepening. Dipwell 6, on the driest part of Rindle, markedly shallows from -110 cm before plateauing to ~30 cm in spring.

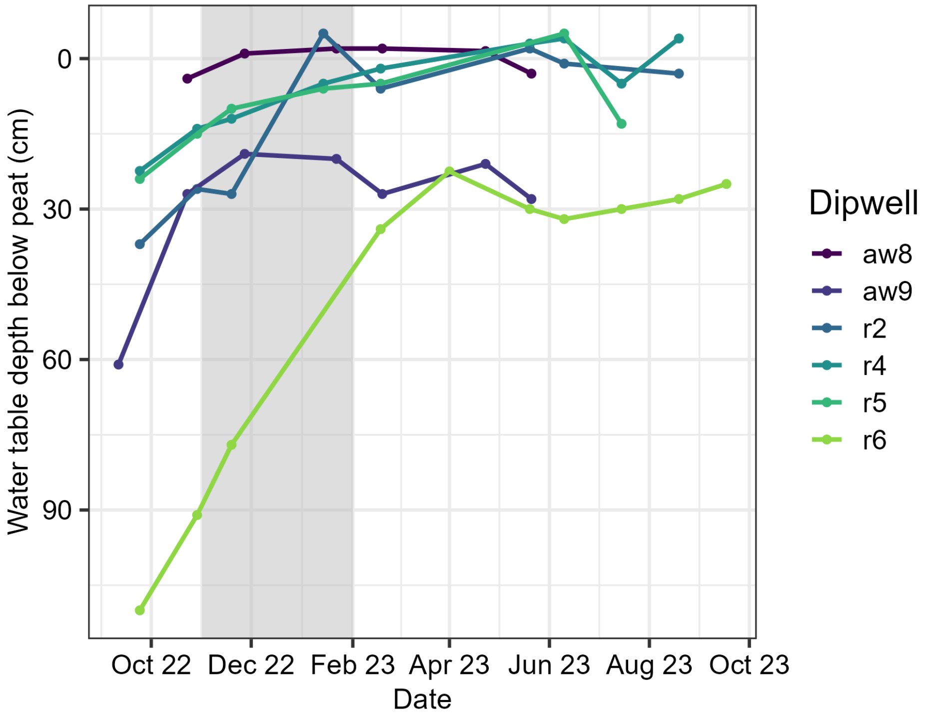


Figure 14: Timeseries showing water table depth at dipwells at Astley (aw-) and Rindle (r-) 11/09/2022–21/05/2023 and 24/09/2022–19/08/2023 respectively. The area shaded grey shows approximately when peat bunds were constructed at Rindle.

4.6 Soil moisture at Rindle

There was a strong positive exponential relationship between *Molinia* and soil moisture (Figure 15), best described by this model:

$$\ln(\widehat{Mc +\ 0.1}) = -15.12689 + 0.20743(SM)$$

where Mc is the percentage of *Molinia* and SM is soil moisture. For each percent increase in soil moisture, *Molinia* was predicted to increase by 0.20743% ($R^2_{multiple}$=0.5973, t=3.445, df=8, p=0.00876). The model that best explained the relationship between *Sphagnum* and soil moisture was:

$$\widehat{Sph} = -0.9791 + 2.259 \times 10^{-38}(e^{SM})$$

where Sph is *Sphagnum* percentage cover and e is Euler's number. There was a strong positive exponential relationship ($\beta(\%)= 2.259 \times 10^{-38}$, $R^2_{multiple}$=0.6184, t=-0.126, df=8, p=0.00698).

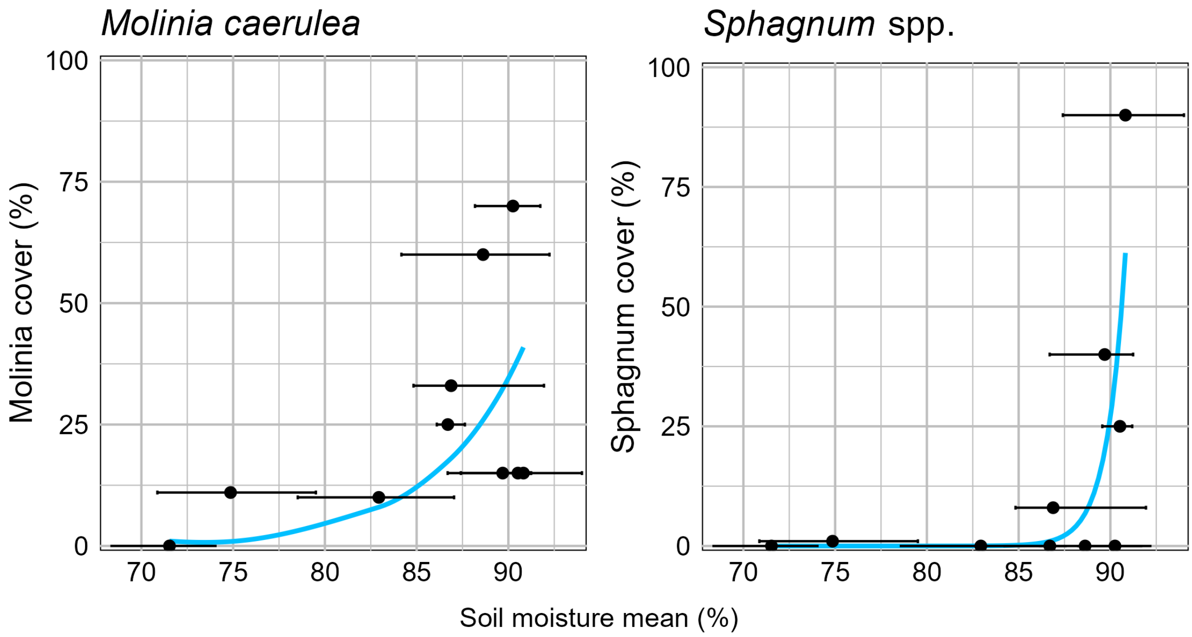


Figure 15: Relationships between soil moisture mean and *Molinia* and *Sphagnum* cover at Rindle.

4.7 Peat characteristics

Table 2: Summary statistics including standard deviation for soil moisture, Soil Organic Matter, nutrients and pH at Rindle.

Peat variable	Minimum	Mean	Max	SD
Bulk density (g/cm^3)	0.06178	0.14767	0.33327	0.05860174
Moisture (%)	68.31	85.73	94.01	6.907083
SOM (%)	71.74	91.25	98.29	6.431179
pH	3.5	3.817	4.6	0.2569969
Bromide (mg/L)	0.6572134	2.38232	5.14681	1.404477
Carbon (%)	32.9	46.4	52.75	3.588591
Chloride (mg/L)	76.24671	141.503	266.767	40.97026
Fluoride (mg/L)	10.627682	20.3291	55.64407	14.71398
Hydrogen (%)	3.56937337	4.937	6.1	0.9552574
Nitrate (mg/L)	0.7201626	3.34477	30.9628	6.220891
Nitrogen (%)	0.603	1.271	1.784	0.2478819
Phosphate (mg/L)	2.098699	30.2208	115.68	32.47105
Sulphate (mg/L)	54.36405	112.215	189.202	32.70107
Sulphur (%)	0.02912948	0.2353	0.4601	0.1254633

4.7.1 Nutrients

Sphagnum had non-linear positive relationships with carbon, sulphur and hydrogen (Figure 16A-C). *Molinia* increased linearly with bromide (Figure 16D) and non-linearly with nitrate (Figure 16E).

Interactions between peat characteristics are in Appendix A.5.

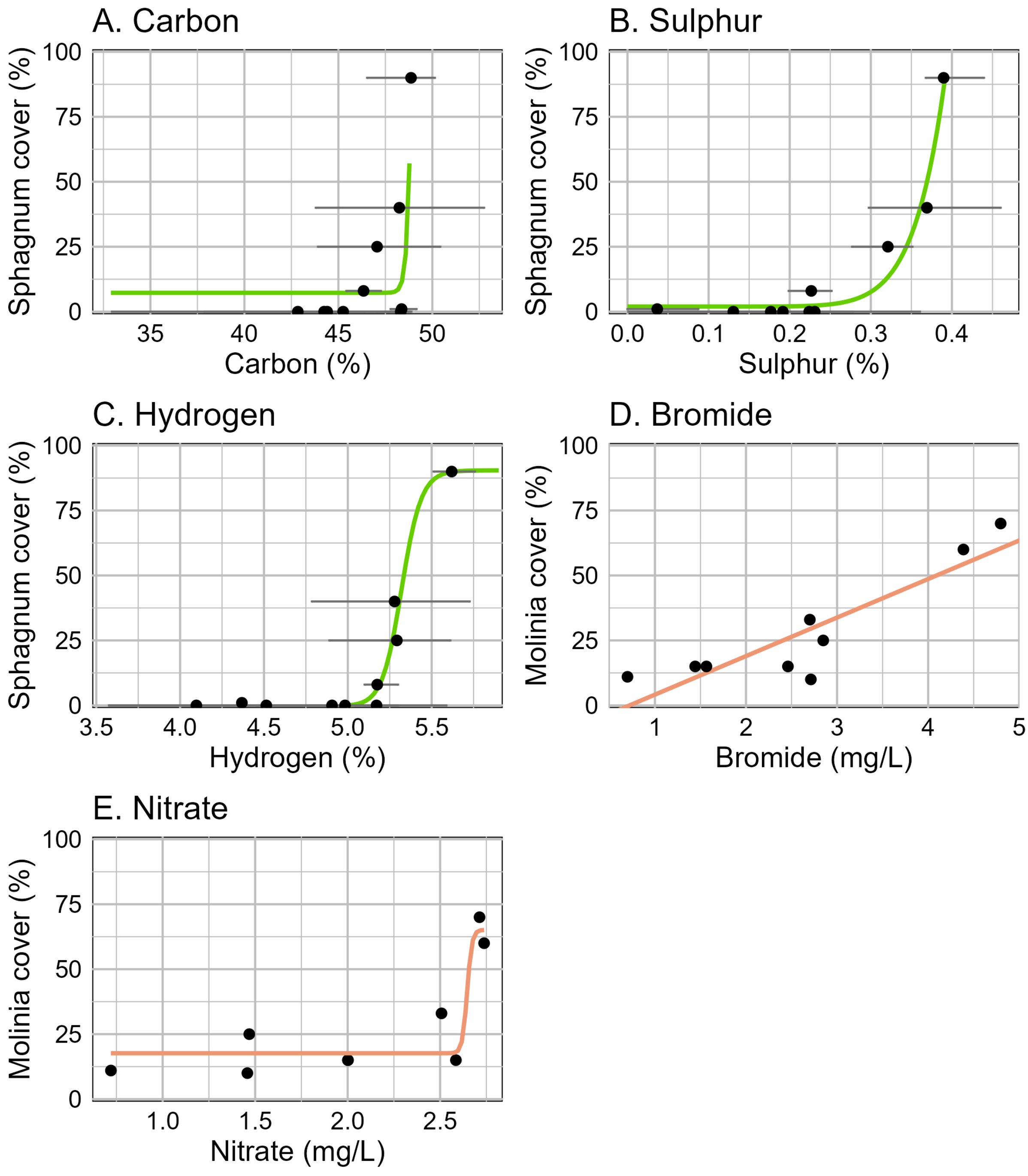


Figure 16: Significant relationships between nutrients and *Sphagnum* and *Molinia* cover.

Table 3: Trends between *Sphagnum* and *Molinia* cover and nutrients. 4PL=Four Parameter Logistic Regression.

Plant	Variable (%)	Model	p-value	β(% cover)	$R^2_{multiple}$
Sphagnum	Carbon	4PL			0.7812
Sphagnum	Sulphur	4PL			0.9601
Sphagnum	Hydrogen	4PL			0.9691
Molinia	Bromide	Linear	0.00137	14.831	0.7894
Molinia	Nitrate	4PL			0.8813

4.7.2 Bulk density

Effects of *Sphagnum* and *Molinia* cover on bulk density were not statistically significant ($p = 0.138, 0.304376$ respectively) (Appendix A.4).

There was a strong negative effect of soil moisture on bulk density (β(g/cm³)=-0.007418, p=0.00008256).

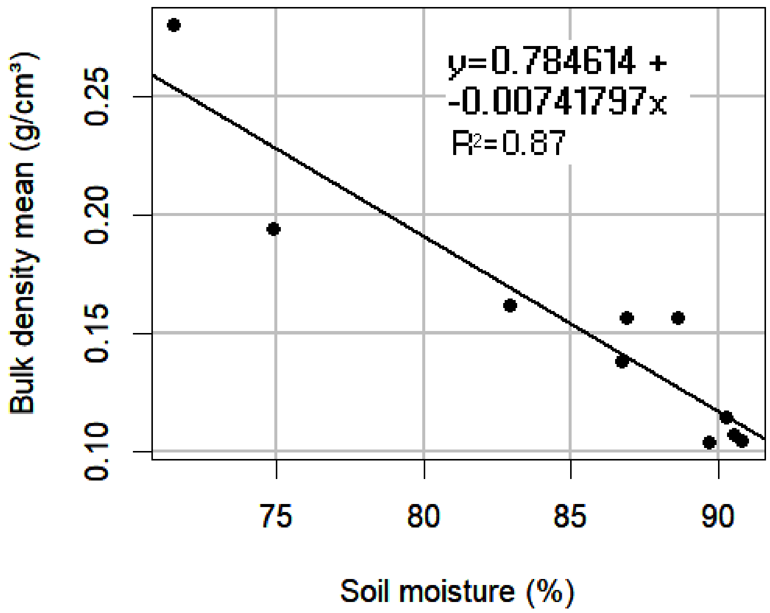


Figure 17: Linear correlation between soil moisture and bulk density.

4.7.3 pH

No relationships between *Sphagnum*, *Molinia* and pH were detected. Peat was acidic and within the normal range (3.6-4.1) for a bog. (Rodwell, 1991) has M18 soil pH as 4.0 (3.3-4.7).

4.8 National Vegetation Classification

Table 4 shows the top ten NVC coefficients for each site. The high frequency of *Calluna vulgaris* resulted in sites assigned as heathland (H), and high *Molinia* was reflected in sub-community frequency. Control and treated sites did not differ greatly in community codes.

Table 4: NVC classifications by site. Higher coefficients show stronger similarity to that community.

Site	**Community Code**	**Community Name**	**Coefficient**
AC	H9e	*Calluna vulgaris-Deschampsia flexuosa* heath, *Molinia caerulea* sub-community	43.24
	H2c	*Calluna vulgaris-Ulex minor* heath, *Molinia caerulea* sub-community	38.28
	M25a	*Molinia caerulea-Potentilla erecta* mire, *Erica tetralix* sub-community	37.04
	M16a	*Erica tetralix-Sphagnum compactum* wet heath, typical sub-community	34.98
	H2	*Calluna vulgaris-Ulex minor* heath	34.48
	W4c	*Betula pubescens-Molinia caerulea* woodland, *Sphagnum spp.* sub-community	34.06
	H2a	*Calluna vulgaris-Ulex minor* heath, typical sub-community	33.61
	M15c	*Scirpus cespitosus-Erica tetralix* wet heath, *Cladonia spp.* sub-community	32.56
	H3a	*Ulex minor-Agrostis curtisii* heath, typical sub-community	32.32
	H3	*Ulex minor-Agrostis curtisii* heath	31.58
AT	H2c	*Calluna vulgaris-Ulex minor* heath, *Molinia caerulea* sub-community	40.98
	H9e	*Calluna vulgaris-Deschampsia flexuosa* heath, *Molinia caerulea* sub-community	40.91
	H3a	*Ulex minor-Agrostis curtisii* heath, typical sub-community	40.31
	H2	*Calluna vulgaris-Ulex minor* heath	39.93
	H2a	*Calluna vulgaris-Ulex minor* heath, typical sub-community	39.64
	H3	*Ulex minor-Agrostis curtisii* heath	38.98
	H4	*Ulex gallii-Agrostis curtisii* heath	34.29
	H12a	*Calluna vulgaris-Vaccinium myrtillus* heath, *Calluna vulgaris* sub-community	33.76
	H4a	*Ulex gallii-Agrostis curtisii* heath, *Agrostis curtisii-Erica cinerea* sub-community	33.59
	H2b	*Calluna vulgaris-Ulex minor heath, Vaccinium myrtillus* sub-community	33.59
RT	H2c	*Calluna vulgaris-Ulex minor* heath, *Molinia caerulea* sub-community	38.61
	H2	*Calluna vulgaris-Ulex minor* heath	38.59
	H2b	*Calluna vulgaris-Ulex minor* heath, *Vaccinium myrtillus* sub-community	37.96
	H3a	*Ulex minor-Agrostis curtisii* heath, typical sub-community	36.04
	H2a	*Calluna vulgaris-Ulex minor* heath, typical sub-community	34.72
	H9e	*Calluna vulgaris-Deschampsia flexuosa* heath, *Molinia caerulea* sub-community	34.04
	M16a	*Erica tetralix-Sphagnum compactum* wet heath, typical sub-community	32.52
	M25a	*Molinia caerulea-Potentilla erecta mire, Erica tetralix* sub-community	32.09
	H3	*Ulex minor-Agrostis curtisii* heath	31.98
	W4c	*Betula pubescens-Molinia caerulea woodland, Sphagnum spp.* sub-community	31.79

5 Discussion

This study aims to explore the efficacy of mulching *Molinia caerulea* to reduce its dominance and improve restoration of a degraded cutover raised bog. Does mulching *Molinia* bring the site closer to its restoration target? This question is explored by comparing vegetation assemblage between sites, considering the impact of hydrology and how vegetation interacts with peat characteristics.

1. Are there differences in the vegetation communities present at each site?

The similarities and differences in the vegetation communities at each site are broadly in line with expectations.

***Molinia* was frequent and abundant on all sites** (Figure 7), **but significantly higher at the control site** (Figure 5). At Astley Control, *Molinia* was above 45% in all quadrats, whereas treated sites had more range, with some quadrats having lower *Molinia* cover (Figure 7). This corresponds to previous research, where cutting reduced *Molinia* dominance (Marrs *et al.*, 2015).

The size and shape of *Molinia* differed between sites. *Molinia* height was significantly shorter at the treated sites. The ground was more even and there was more bare peat (at Astley) and bog pool (at Rindle). At AC, the grass was very tussocky. Similar to management at blanket mire in Abergwesyn (Daggett, 2015), cutting reduced the tussocky structure (Figure 18). Defoliating *Molinia* reduces leaf production and nutrient storage long term, resulting in less bud formation the following year (Taylor *et al.*, 2001). The tussock stores nutrients (Taylor *et al.*, 2001), so its removal by flailing results in *Molinia* growing less vigorously for several years (Perry, 2015). The reduced tussocky structure at treated sites demonstrates the short term efficacy of flailing.

There was more biomass overall at AC (Figure 6). The positive correlation between *Molinia* height and percentage cover (Figure 11) indicated that shorter *Molinia* also takes up less space laterally. **The higher cover and size of *Molinia* at the control site reduced space for other plants**, so it dominated, corresponding to research on blanket bog, where *Molinia* cover had an inverse relationship with bog indicator species cover (Pilkington, 2015). At treated sites, it was smaller and weaker, so within-quadrat diversity was higher (Figure 9) as other plants had space to grow. Previous research on cutting *Molinia* also showed a reduction in *Molinia* cover and increased species diversity (Marrs *et al.*, 2015).

Molinia caerulea had more dry shoots (plant litter) at AC, visible in Figure 19 as the paler

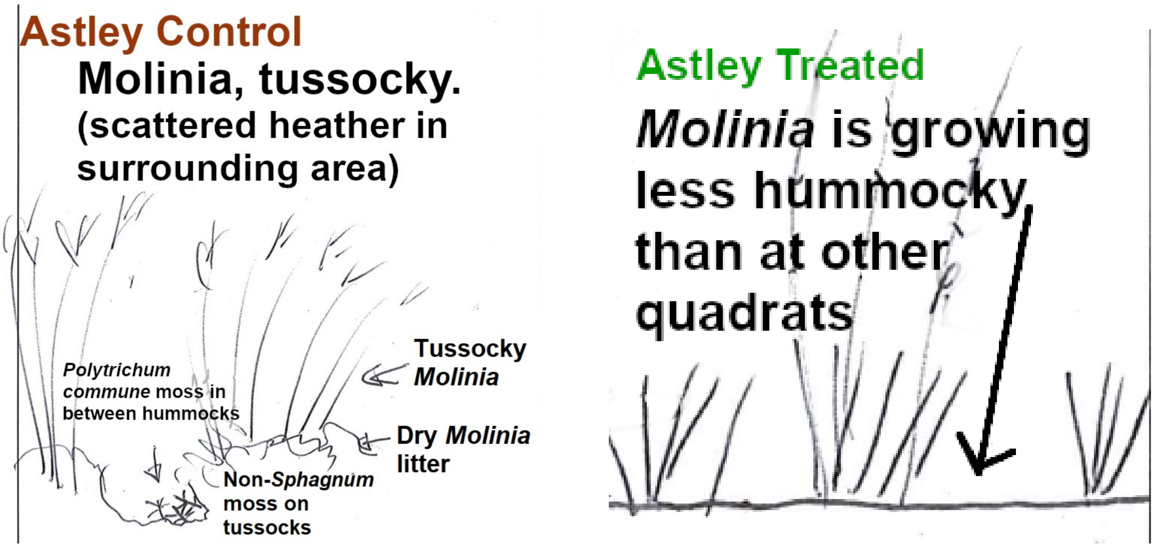


Figure 18: Field sketches showing difference in *Molinia* shape between sites.

colour and in Figure 6 as 'dead plant matter'. Thick *Molinia* litter build up prevented the growth of other plants in a previous moorland study (Underdown & Meade, 2015).

Within-quadrat SDI is higher at AT than at RT (Figure 9): there is more chance of selecting two different species at random on a small scale (1 m^2). However, site SDI is higher at RT because on a broad scale diversity is higher, likely due to topographic variations like the dry strip in the centre (Keightley & Rogers, 2021). On a finer scale heterogeneity is higher at AT, whereas at RT more species are grouped together in more homogenous stands.

TWINSPAN mostly grouped quadrats from the same sites together, demonstrating the difference in vegetation composition between sites (Figure 10). AC is characterised by *Molinia* domination, and is most different to Rindle, which is diverse and has *Sphagnum*. AT appears to be the midpoint between AC and RT; where vegetation is more diverse and less *Molinia*-dominated than at AC, but less so than RT.

2. Is there a relationship between water table, soil moisture and abundance of wetland vegetation and *Molinia*?

Results show strong interactions between wetland vegetation, *Molinia*, water table and soil moisture. The water table was significantly lower at Astley than Rindle (Figure 13, 4) due to long-standing problems with blocking drainage (Thomas, 2015).

The higher water table at Rindle corresponded to reduced *Molinia* domination. Large areas of Rindle had standing water. *Molinia* is weaker under waterlogged conditions or in standing water as it cannot oxygenate its root environment effectively, so grows less tussocky and dense (Anderson, 2015). This was observed at Rindle, where

Figure 19: Astley Control and Treated; less dry *Molinia* litter at the Treated site.

Molinia cover took up less space and was less dominant. Although both AT and RT were flailed, *Molinia* cover was lower at Rindle (Figure 7). The difference demonstrates the importance of a high water table in weakening *Molinia*.

Results show higher water table increases *Sphagnum*. Because water table at Rindle is close to or above the peat surface (Figure 13), it had more *Sphagnum* than either Astley sites. *Sphagnum cuspidatum*, the most abundant *Sphagnum* species at Rindle, indicates a stable, high water table (JNCC, 2004). Although two Control quadrats had *Sphagnum*, cover was low and peat was noted as uncharacteristically damp. This corresponds with previous research on *Sphagnum* recolonisation on cutover bog in Canada. Areas where *Sphagnum* recovered were characterised by high water table (mean -24.9±14.3 cm) (Price & Whitehead, 2001). *Sphagnum* has a soil-water pressure threshold of -100cm below which it cannot extract water from peat. Lower water table decreases pressure (ibid.). Although soil-water pressure was not analysed in this study, because at Rindle water table was higher than Astley, soil-water pressure was likely higher, thus able to support *Sphagnum*.

Some *Sphagnum* plugs have been planted at Astley Treated, however no *Sphagnum* appeared in quadrats despite lower *Molinia* cover. This appears to be partly due to the lower water table. However, some wetter peat and bog pools at Astley, which could not be surveyed for safety reasons, had *Sphagnum cuspidatum* (Figure 20), indicating parts of Astley had a high stable water table (JNCC, 2004)). The restriction of *Sphagnum* to pools corresponds to previous research. Modelling by Schouwenaars (1990) found that *Sphagnum* surrounded by vascular plants on bare peat is vulnerable to drying out, but open water alleviates the risk. The high water table at Rindle enabled *Sphagnum* to grow larger and spread out more on the site, whereas at Astley it was smaller and infrequent.

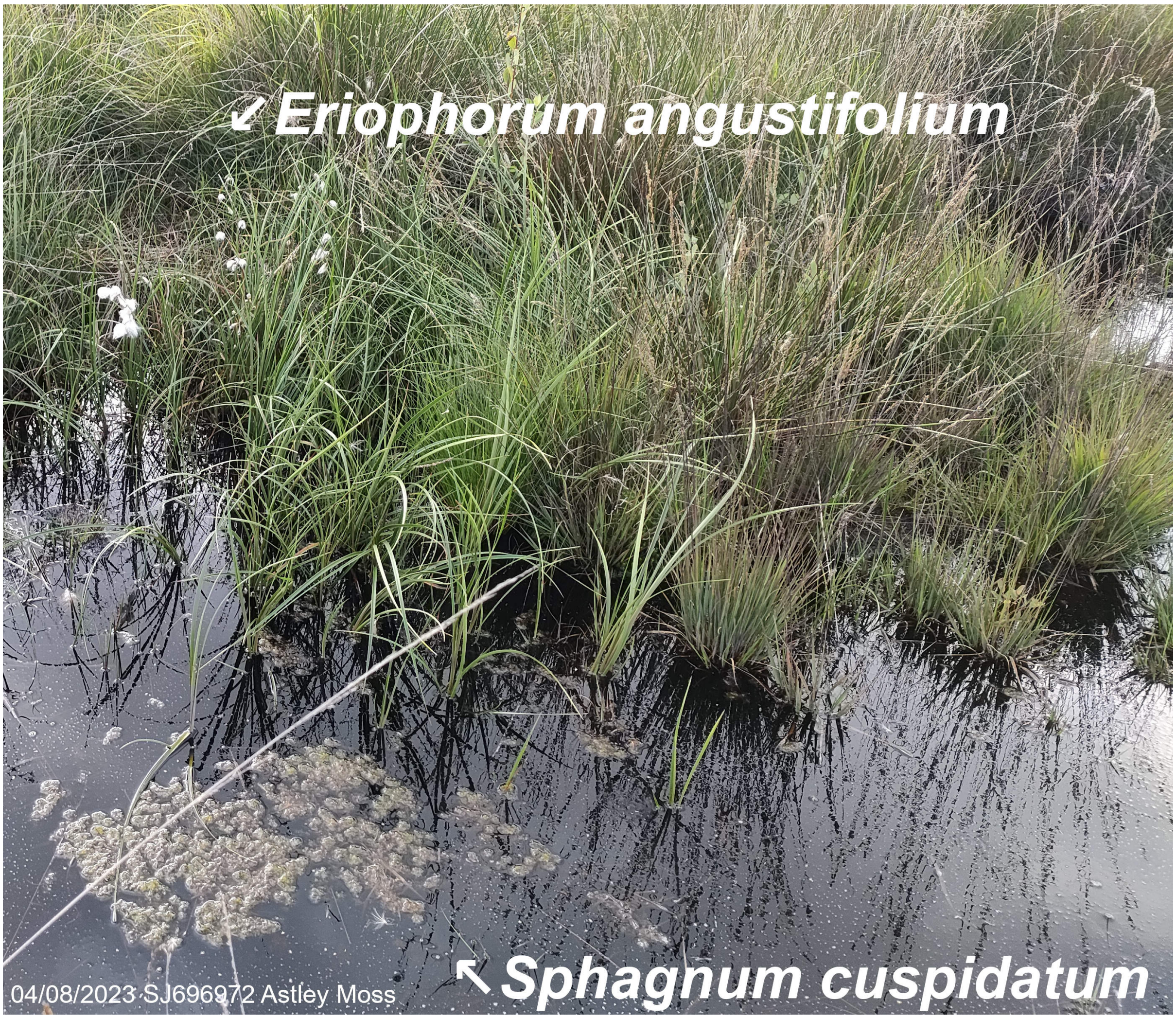


Figure 20: *S. cuspidatum* and *E. angustfolium* in bog pool at Astley.

Soil-moisture must be high enough to sustain sufficiently high pressure, which was ≥50% in Price & Whitehead (2001). At Rindle the relationship between soil moisture and *Sphagnum* cover followed a positive non-linear trend (Figure 15). There appeared to be a threshold around 85% soil moisture below which there is very little *Sphagnum*, and above which *Sphagnum* cover increases. Some areas at Rindle with high soil moisture do not have *Sphagnum*; this is expected as other factors are required for *Sphagnum* growth, such as propagule sources from which it can establish (Minayeva *et al.*, 2017).

Extensive standing water at Rindle enables *Sphagnum* to grow thicker and be competitive against *Molinia*. Figure 21 shows how *Molinia* culms (aerial stems) are short and scattered within the *Sphagnum*. This was previously observed on blanket moorland by Jepson (2015). When water table is close to or above the peat surface, humidity is high enough for *Sphagnum* to flourish under and between *Molinia*. Therefore, lower *Molinia* cover at RT than AT is due to higher water table, not only because waterlogged soil weakens the grass but also as standing water allows *Sphagnum* to grow so thickly it restricts the tussocky growth of *Molinia*. Jepson (2015) states bog restoration will follow after peat hydrology is restored, and this study confirms the importance of hydrology in restoring peat-forming vegetation.

Figure 21: *Sphagnum* growing thickly, so *Molinia* culms are smaller.

Although Rindle had the lowest proportion of *Molinia* (Figure 5), it was still abundant and dominated some areas. Quadrats rt6/26 and rt9/29 were inundated, yet *Molinia* cover was relatively high, and diversity was low. Vegetation composition was even grouped with an AC quadrat using TWINSPAN (Figure 10). A possible mechanism for this is lack of established *Sphagnum* in that area to compete with *Molinia* after it was cut. Although a high water table weakens *Molinia*, in the absence of competitive wetland vegetation, it grows larger and the tussocks get drier (Gogo *et al.*, 2011). Early after mulching, *Sphagnum* establishment should be supported by high water table and possibly planting, so it can compete with *Molinia*.

It seems that some *Molinia* provides growth for *Sphagnum* to grow out of the bog pool. *Sphagnum cuspidatum* starts off in the water and uses *Molinia* tussocks as a refuge to rise above the water (Figure 22). A study on cutover peatland in Cheshire found that although complete inundation reduced *Molinia* competition, *Sphagnum* could not always establish in large pools due to waves. *Sphagnum* cover expanded best on waterlogged rather than inundated tussocks, as tussocks provided a growing surface (Meade, 1992).

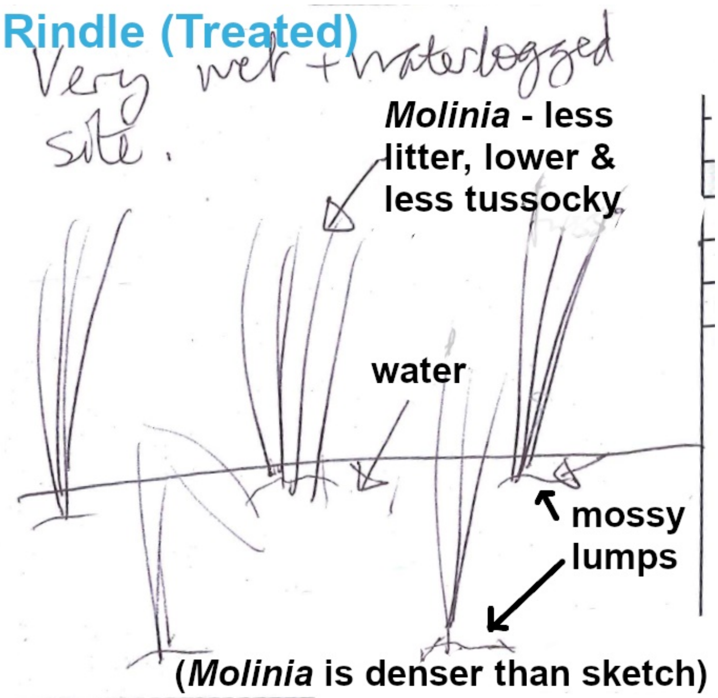


Figure 22: Field sketch depicting *Sphagnum* growing out of the water on inundated *Molinia* tussocks.

Both Astley sites had high *Hypnum jutlandicum* cover, with the highest proportion at Astley Treated. In TWINSPAN analysis, it was the indicator species characterising groups containing Astley Treated quadrats (Figure 10). When hypnale mosses are present instead of *Sphagnum*, this can indicate drying out of the mire (JNCC, 2004). The difference in moss types between Astley Treated and Rindle Treated demonstrates the importance of blocking sites from external drainage to restore wetland vegetation. However, as Rindle had pre-existing *Sphagnum* (Keightley & Rogers, 2021), this may have been a confounding factor as in past flailing studies (Pilkington, 2015).

The positive effect of soil moisture on *Molinia* cover at Rindle (Figure 15) was unexpected as *Molinia* prefers drier soils (e.g. (Meade, 1992)). There are possible reasons for this. Soil moisture was only measured within Rindle, so the relationship only shows within-site variation. The survey was carried out within the year water table was raised (Figure 4.5), so *Molinia* may not have yet adjusted to corresponding moisture changes. Other factors may have increased *Molinia* growth in some areas, such as water table fluctuation aerating roots (Loach, 1966).

AT was more diverse and had more wetland vegetation than AC. This indicates mulching improves conditions for wetland vegetation, even when water table is not consistently close to the surface. Lower *Molinia* cover after mulching means less water is lost to evapotranspiration (Pilkington, 2015), so more moisture remains in the peat. A previous study on blanket bog in the South Pennines found flailing raised the water table (Pilkington, 2015). Flailing reduces *Molinia* dominance and increases wetland species in the short term, and at Rindle likely enabled *Sphagnum* to compete with *Molinia*. *Sphagnum* reduces water table fluctuations in dry periods by increasing water storage capacity at the peat surface (Schouwenaars, 1990), so if flailing increases *Sphagnum* growth it may stabilise water levels.

3. Is there a relationship between peat conditions and vegetation community at Rindle Moss?

Both *Molinia* (Taylor *et al.*, 2001) and *Sphagnum* (Müller *et al.*, 2023) are engineer species that can influence the nutrients in the peat around them for more favourable conditions for themselves. Assessing nutrients will help determine how much of a functioning ombrotrophic bog Rindle is, and exploring vegetation-peat relationships can highlight mechanisms behind vegetation distribution. There were some relationships between peat conditions and vegetation composition at Rindle, however some results were unexpected. Some peat characteristics did not show significant relationships with vegetation.

Bulk density was expected to increase with *Molinia* cover and decrease with *Sphagnum* (Gogo *et al.*, 2011), however results did not show any significant relationships. There may no effect, and it is also possible the sample size was too small to show any effect (Visentin *et al.*, 2020), especially given the variability in many factors between quadrats.

Nitrate and *Molinia* had a non-linear positive relationship (Figure 16E), which corresponds with (Loach, 1966) *Molinia* increases with increasing nitrogen and it increases decomposition rates and thus nutrients (Gogo *et al.*, 2011).

There was a strong positive relationship between bromide and *Molinia* (Figure 16D), which was interesting as bromide was not discussed in peatland vegetation literature. Research on previously drained upland mire in Wales showed increased bromide concentration after disturbances including rewetting and drought, as a result of increased solubility (Hughes *et al.*, 1996). This could indicate that higher *Molinia* cover occurred where water table had experienced more fluctuations, consistent with Taylor *et al.* (2001), who report *Molinia* favours areas with groundwater movement. Bromide is associated with biological cycles and humification in peat. It leads to higher Organic Matter decomposition (Hughes *et al.*, 1996). This may indicate increased OM decomposition in areas with higher *Molinia* as described by Gogo *et al.* (2011), however bromide, SOM and *Molinia* did not correlate at Rindle (Appendix A.5), and more data is needed.

The positive relationship between *Sphagnum* and carbon (Figure 16A) demonstrates active peat-building at Rindle. *Sphagnum* decomposes carbon slowly compared to vascular plants by inhibiting enzymatic activities and releasing sphagnan (Müller *et al.*, 2023). Peat Carbon percentage increases with *Sphagnum* cover, because C mineralisation is reduced. This corresponds with decomposition experiments where C did not decrease in *Sphagnum* litter (Müller *et al.*, 2023). Peat builds when biomass production outweighs decomposition (Müller *et al.*, 2023). At Rindle, carbon in peat increased with *Sphagnum* cover, suggesting that *Sphagnum* is sequestering carbon by actively building peat.

Sphagnum cover correlated positively with sulphur concentration (Figure 16B), but no interaction was found between *Sphagnum* and sulphate. Bog surface waters contain more sulphur than sulphate, partly due to *Sphagnum* uptake (Bottrell & Novak, 1997), possibly accounting for the increase in sulfur with increasing *Sphagnum* cover.

The positive relationship between *Sphagnum* and Hydrogen (Figure 16C) is likely because *Sphagnum* releases Hydrogen ions into peat water. Hydrogen forms inorganic acids, which combine with the peat to form organic acids (Champion, 2021).

Although no trend between *Sphagnum* and pH was found, plots containing *Sphagnum* had a pH range of 3.7-4.1, which is above the pH 3.5 threshold below which Sphagnum suffers negative effects (Carroll *et al.*, 2009).

These relationships between *Sphagnum* growth and nutrients show normal bog function at Rindle.

4. Does mulching *Molinia* bring the vegetation community closer to the restoration goal (M18: *Erica tetralix-Sphagnum papillosum* raised mire)?

The NVC is useful to compare vegetation assemblages to existing habitats, giving an estimate of how similar environmental characteristics and vegetation are to the restoration aim. It provides a reference for what vegetation grows together, under what habitat and environmental conditions (Pescott *et al.*, 2016). Sites under restoration require specific vegetation community targets (JNCC, 2004), which for study sites was M18 because they historically were raised bogs.

The NVC is based on floristic composition, with heaths defined as structurally dominated by sub-shrubs like *Calluna vulgaris* while mires are also composed of bryophytes and herbaceous plants on waterlogged ground (Rodwell, 1991). **No sites were assigned M18: *Erica* – *Sphagnum* mire** based on floristic composition, as no sites yet have the vegetation assemblage or structure to be classified as healthy raised bogs. Also, none were assigned M1-3, M17, M19-21, other NVC communities on raised bog. Sites were mostly assigned as heaths, likely due to the prevalence of *Calluna vulgaris*. [*Cladonia* sub-community can indicate drying, with *Hypnum* rather than *Sphagnum* mosses (JNCC, 2004); Astley Control had this community as a result (4).] Communities that were assigned like M15c, M16a, M25a and the dry heaths (H*) show sites are closer to 'degraded raised bog' (JNCC, 2004).

M25a and W4 are communities associated with M18. M18 is found closer to the stagnant centre of a raised bog, while M25a and W4 are zonations towards the margins where it drains more freely and is less ombrotrophic (Figure 23). *Molinia* usually dominates these areas. This suggests water is not sufficiently stagnant for M18 mire. Rindle was inundated with stagnant water, however only for a few months, so may transition to M18 if drainage remains impeded. The fact that sites have similarities to M25 and W4, associated with drier margins of M18, is a good sign as it shows some features aligning with the goal.

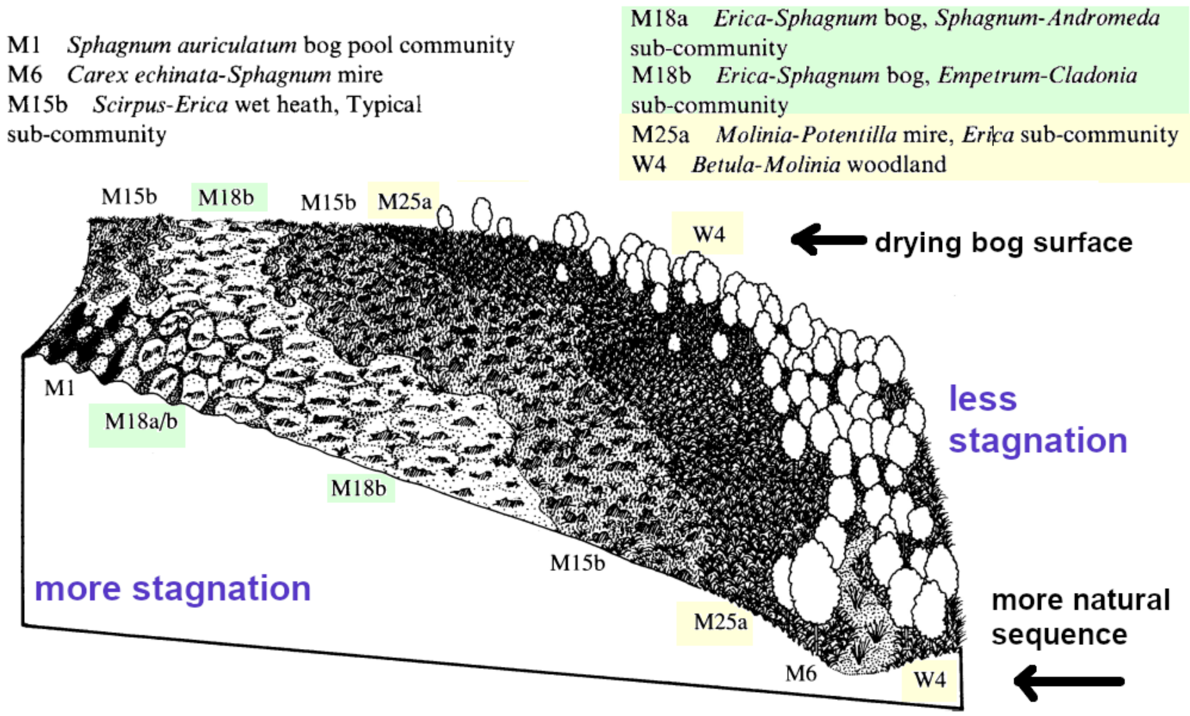


Figure 23: Raised bog zonation, adapted from (Rodwell, 1991).

It is hard to assess whether flailing brought the sites closer to M18, although it definitely decreased *Molinia* dominance in the short term, bringing sites closer to M18 as that is not dominated by *Molinia*. Decreasing *Molinia* abundance and litter was necessary to increase space for a higher abundance of wetland plants and diversity (Figure 9), corresponding with previous research where weakening *Molinia* increased diversity (Marrs *et al.*, 2015). Mulching appears to help increase *Sphagnum* cover where water table is sufficiently high and *Sphagnum* sources exist. However, mulching alone will not bring the sites to M18 condition. Water table needs to be raised site-wide and remain stable.

There are limitations in using NVC to monitor restoration. It classifies based only on floristic composition (Elkington *et al.*, 2002), so environmental characteristics and vegetation cover are not considered. While species richness did not differ between sites (Table 1), percentage cover of key species did (Figure 7). NVC groupings are not very repeatable on a community level, especially for mires/wet heaths which share constant species or rely on species-level identification of *Sphagnum* (Hearn *et al.*, 2011). It best assesses homogenous stands, however sites had high heterogeneity: there was small-scale topographical variation like between inundated and dry peat at Rindle.

All sites were assigned several *Molinia caerulea* (sub-)communities, demonstrating its frequency on all sites. However, *Molinia* is not a key indicator species in many NVC communities. The NVC is community level and descriptive, and not exhaustive, so may not be the best metric for focusing on specific management impacts. NVC analysis did not give useful information on the effect of mulching, as control and treated sites did not differ greatly in community code results (Table 4).

Rodwell (Rodwell, 2006) cautions against using the NVC prescriptively and seeing sites that do not fit the NVC well as sub-standard, as nature varies more than can be summarised in floristic tables. Comparing directly to NVC is restrictive as it is only based on fixed references (Pescott *et al.*, 2016). M18 is generally the target for degraded lowland raised bogs, however another recovering bog at Danes Moss aligned with M2 and M21, highlighting the need for NVC goals to be broad, especially early in recovery (Meade, 2015).

As the NVC is a phytosociological classification (plant-community-based), it relies on specific species to define each community. For example, cross-leaved heath (*Erica tetralix*) is also required for an M18 classification specifically, and as this grows on neighbouring parts of Astley this may move to the study site eventually.

The condition of protected sites is monitored broadly based on how well they meet specific objectives described in JNCC (2004). Comparing each site against JNCC targets for raised bog (JNCC, 2004) (5) highlights restoration progress and areas for improvement across the sites. The reduction in *Molinia* cover at treated sites demonstrates the efficacy of mulching in reducing vascular plant domination. No sites met target 2, as out of positive vascular plant indicator species, only *Calluna vulgaris* was frequent on all sites. Common cotton-grass was sporadically spotted on both Astley and Rindle, so will possibly spread with time if *Molinia* remains weak, and if water table is increased at Astley, similar to when Cotton-grasses spread after rewetting and *Molinia* reduction at the core of Astley Moss in 2010 (Thomas, 2015). The current absence of these plants, and specialised bog species, could be remediated by transplanting. It is also important to remember that ombrogenous bog is a climax habitat, so sufficient time could be one of the most important requirements for effective restoration (Money & Wheeler, 1999).

Table 5: Sites assessed against vegetation indicator targets for raised bog in JNCC (2004). Frequency classes based on number of quadrats they are in: <2=rare, 3-4=occasional, 5-6=frequent, >6=constant.

	Target	Astley Control	Astley Treated	Rindle Treated
1	No one vascular plant species >50% cover.	Median *Molinia*:		
		77.5%.	35%	15%
2	At least three of the following constant: *Calluna vulgaris, Erica tetralix, Eriophorum angustifolium, E. vaginatum* and *Trichophorum cespitosum*.	Calluna vulgaris:		
		Frequent (6/10 quadrats).	Constant (7/10).	Frequent (6/10).
			Cotton grasses spotted on site but not constant; no *E. tetralix* or *T. cespitosum* observed.	
3	Specialised bog species (e.g. round-leaved sundew) frequent.	Absent.		
4	*Sphagnum cuspidatum* at least occasional.	Absent in quadrats; spotted in bog pools.		Occasional (4/10).
5	>20\% combined cover of at least two of these *Sphagnum* species: *S. capillifolium, S. magellanicum, S. papillosum, S. tenellum*.	Out of these species, Rindle had one quadrat with a small amount of *S. papillosum*. A comprehensive *Sphagnum* survey would better ascertain species-level differences however no sites appear to meet this target.		
6	*Polytrichum* mosses no more than occasional.	Occasional (4/10)	Frequent (5/10).	Occasional (4/10).

The absence of *Sphagnum* in Astley Treated quadrats may have concerning implications on the effects of mulching alone on *Sphagnum*. While *Molinia* dominance at Astley Control evidently reduced species diversity, *S. fimbriatum* grew on some tussocks where peat seemed damper (Figure 24). *Molinia* thatch has been observed providing shade and retaining humidity necessary for *Sphagnum* growth on degraded blanket mire (Jepson, 2015). Flailing *Molinia* without raising water table may dry out peat and flatten the ground, removing the microtopographic and microclimatic variation provided by *Molinia* tussocks that is also reported on blanket mire by Jepson (2015). However, because bog pools at Astley provide refuges for *Sphagnum* and cotton-grasses to grow, this may help.

Figure 24: *S. fimbriatum* and *P. commune* on *Molinia* tussock at Astley Control.

TWINSPAN analysis helped visualise the gradient along which vegetation is growing, highlighting hydrological impact Figure 10. It showed mulching bringing the vegetation assemblage closer to a more diverse, less *Molinia*-dominated wetland. Astley treated appears as an intermediate stage between dry and Molinia-encroached, and Rindle which is more *Sphagnum*-rich. Although there are confounding variables like different pre-treatment conditions between sites (Steel *et al.*, 2013), vegetation at AT being slightly closer in similarity to Rindle means conditions like soil moisture are more suitable for wetland vegetation growth. This could indicate mulching helps sites move towards a raised bog vegetation assemblage, which may later become M18.

TWINSPAN clustering of quadrats, as well as soil moisture and peat characteristic results, demonstrates the relative importance of each of these factors, informing future management. It assists ecological quality assessment as vegetation assemblages arrange themselves along environmental gradients. This could be used to predict successional pathways based on previous information: e.g. that if water table at Rindle remains high, *Sphagnum* is likely to continue to grow (Pescott *et al.*, 2016).

It may be more effective to evaluate the impact of mulching through an ecosystem function approach, rather than solely a vegetation community approach. Peatlands are unique in their processes of accumulating of organic matter, which are impeded when damaged. Therefore, management should focus on restoring this ecosystem process, and guidance like JNCC (2004) reflects this as they highlight the importance of restoring peat-forming capacities. Minayeva *et al.* (2017) explain that abiotic processes and variables (e.g. hydrology) reflect the overall 'health' of the ecosystem, as these factors are closely interlinked with processes of plants that build peat.

Instead of asking "does the vegetation community look more like a healthy raised bog after mulching *Molinia*?" we can now ask "does mulching *Molinia* improve the ecosystem processes at the sites?". Because *Molinia* is less dominant at both treated sites, and plant diversity is higher, mulching appears to improve biodiversity. At Rindle, weakening *Molinia* through mulching gave *Sphagnum* the opportunity to compete with it. However, mulching alone, without raising the water table, does not sufficiently restore peat-forming processes, demonstrated by the lack of peat-forming vegetation at Astley Treated. This corresponds with research (Schouwenaars, 1990) that demonstrates the importance of hydrology in restoring mires.

The NVC is broadly useful, however to properly assess the impact of mulching, TWINSPAN, water table and peat interactions, and qualitative analysis are more indicative of change. While NVC classifies Astley Treated as heathlands, looking at vegetation data shows more details. It shows mulching reduces Molinia dominance and increases diversity, however the hydrological gradient is a strong control on the vegetation assemblage so transition to raised bog through mulching only is not possible.

Further study

Surveying took place the summer after flailing. Previous research shows that although *Molinia* grows back smaller after flailing, after several years it can regain its dominance as tussocks grow to a large size (Pilkington, 2015). Repeated treatments have proved more effective (Marrs *et al.*, 2015) at preventing *Molinia* domination. Vegetation composition and *Molinia* size should be monitored to inform future management. Repeated flailing may be necessary if *Molinia* cover increases again to the detriment of other plants. However, mulching *Molinia* without damaging *Sphagnum* and other sensitive species as they grow may be challenging.

Molinia was mulched, rather than removed, leaving excess nutrients on site. This can support future Molinia growth (Bódis *et al.*, 2021), so research should compare mulching to removing flailed plants from the site.

Repeated vegetation surveys would be useful in assessing how the sites are progressing. In October 2023, the rest of Astley was mulched, so monitoring change and comparing sites cut at different times will be valuable.

Future surveys should list rarer species or those in bog pools (e.g. *Eriophorum angustfolium*), as these are important in determining bog condition despite low cover. Because *Sphagnum* species have different environmental requirements, indicating bog in different conditions, detailed *Sphagnum* surveys will help assess restoration, and at Rindle can be compared to a baseline pre-treatment survey (Keightley & Rogers, 2021).

Analysing peat samples at Astley and comparing them to those at Rindle would demonstrate the impact of hydrology and differing site history on peat nutrients, structure and soil moisture. If repeated over time, it will help further assess complex peat-vegetation dynamics.

As parts of sites were less accessible due to inundation and boggy terrain, this may further hinder access as peat grows; surveying could be enhanced with methods like drone footage identification remote sensing (Simpson *et al.*, 2024).

6 Conclusion

Raised bogs have been degraded by resource extraction, leaving them dried out and threatened by *Molinia* encroachment. Reducing the dominance of this grass is important to restore bog function and support a diverse mire community, and this study aims to explore the effects of mulching *Molinia*.

Mulching caused significant differences in vegetation composition between sites, weakening and reducing *Molinia* abundance, increasing diversity indices, and the growth of wetland vegetation. It is as an effective treatment option to reduce *Molinia* and improve bog function, at least in the short term.

Investigating trends between water table and vegetation also established the importance of hydrology in determining vegetation composition. The increased abundance in *Sphagnum* and decreased *Molinia* at Rindle asserted that a high water table is necessary to support the growth of peat-forming vegetation.

Results to question three demonstrated the interconnection between peat and vegetation, with positive relationships between *Sphagnum*, carbon, hydrogen and sulphur suggesting parts of Rindle were actively building peat. The increase in *Molinia* with nitrate suggests *Molinia* enriches peat, and the positive relationship with bromide highlights a need for further research.

Mulching increased floristic diversity and supported wetland vegetation, suggesting it helps restoration to a raised bog community. Evaluating the success of management should be based in ecosystem function, and this study suggests mulching improves peatland processes, although highlights the need for water table restoration in supporting peat-forming vegetation.

Overall, results from this study are insightful for lowland peat management, an area that lacks research. Mulching *Molinia* reduces its dominance, but should be paired with water table management to increase bog function. The Lancashire Wildlife Trust can use these results to further guide management of their lowland peat.

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A Appendix

A.1 Sample card

Location	Grid reference	Date	Author	Sample no.
			[ ]	

Site and vegetation description

Vegetation height					Mean
Shrub/ small trees:	m	m	m	m	m
Field/ sub-shrub:	cm	cm	cm	cm	cm
Ground:	mm	mm	mm	mm	mm

Total vegetation cover	
Shrub/ small trees:	%
Herb/ sub-shrub:	%
Ground layer cryptograms:	%

Geology		
	Region: NW	
	Altitude: m	
	Sample area: m x m	
	Treatment	**Control**
	Weather	
	Photo?	

Species list and % cover

Figure 25: Vegetation sample card, adapted from p.19 (Rodwell, 2006).

A.2 TWINSPAN

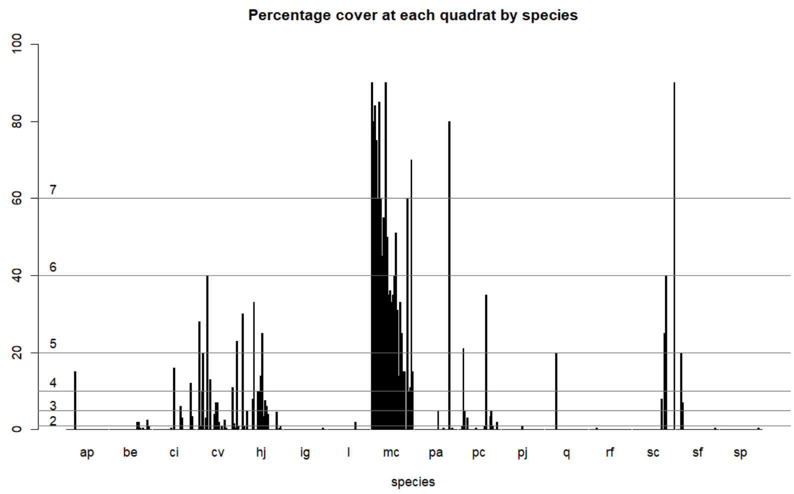

Figure 26: Cut level bands for TWINSPAN displayed on vegetation percentage cover graph.

```
> twintable(tw2)

           000000000000000000000000000001
           00000000000000000000011111111
           00000000111111111111100000111
           000001110000000001111100111
           00001   0000011100001
                   01111
              a                 a      r
           aaacaaaaaaaaaarraaaaatrrrrrrtr
           ccc1cccctctttctttttttt1tttttt1t
           169074587318926923465081273405
 000  ap ----4-------------------------
 000  hj -------3-223335225445421-------
 000  pj --------------------2---------
 0010  q -------5----------------------
 0010 rf -1----------------------------
 0010 sf -----53---------------1-------
 0011 cv ----2456-2-2-54542323211-2--2-
 0011 mc 77767776676657775555544554444-
 010  sc -----------------------3--567-
 0110 ci -----------------1--4322-4----
 0111 be --------------------22212-1--
 0111 ig ----------------------1-------
 0111  l --------------------2--------
 0111 sp ----------------------1-------
 1    pa --------3--------------1-1---7
 1    pc ----253--2--2----1---52---23-2
30 sites, 16 species
```

Figure 27: Pseudospecies (based on abundance band) ordered by TWINSPAN classification.

A.3 Water table

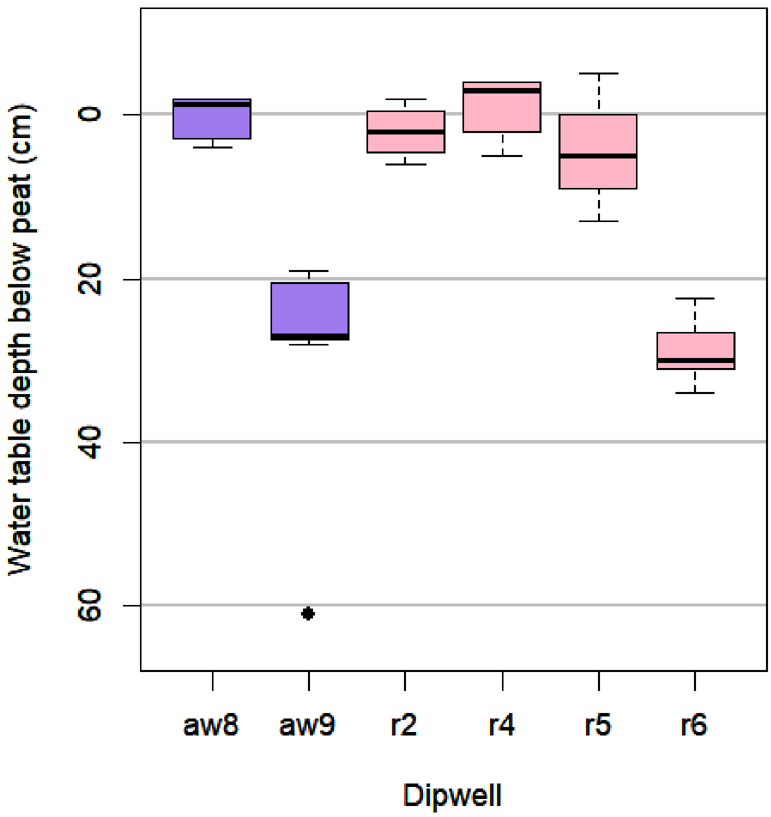

Figure 28: Water table depth by dipwell; Astley are in purple and Rindle in pink. Dipwell Rindle 6 was excluded from analysis for being non-representatively low.

As Figure 28 shows, there is significant difference between dipwells aw8 and aw9 at Astley (Wilcoxon rank test: W=17, p= 0.04284), and aw8 is more similar to Rindle measurements. However, relevance or reliability of aw8 measurements, showing water close to or above the peat surface, is uncertain as there only appeared to be standing water at Astley in small bog pools which were outside the survey areas.

A.4 Bulk density

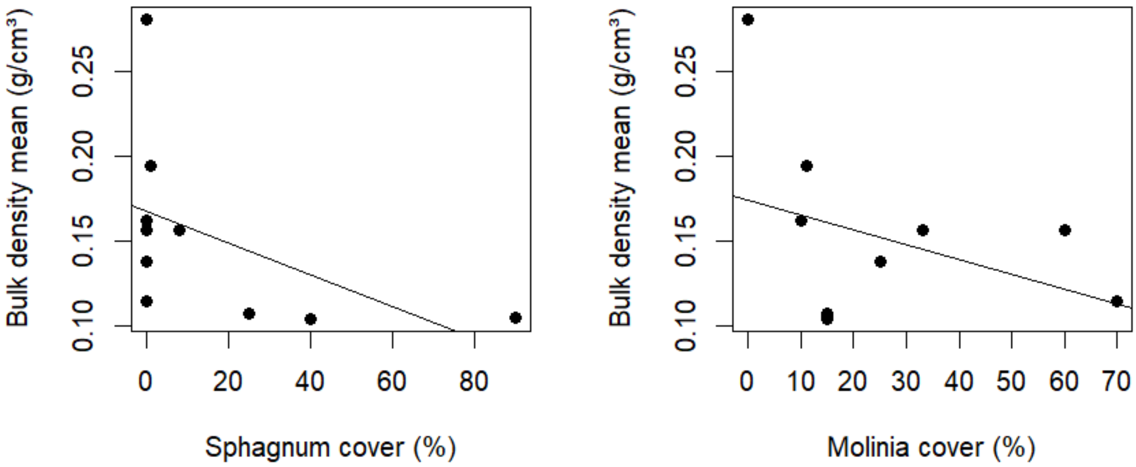

Figure 29: Sphagnum and *Molinia* cover plotted against bulk density mean.

A.5 Correlation matrix

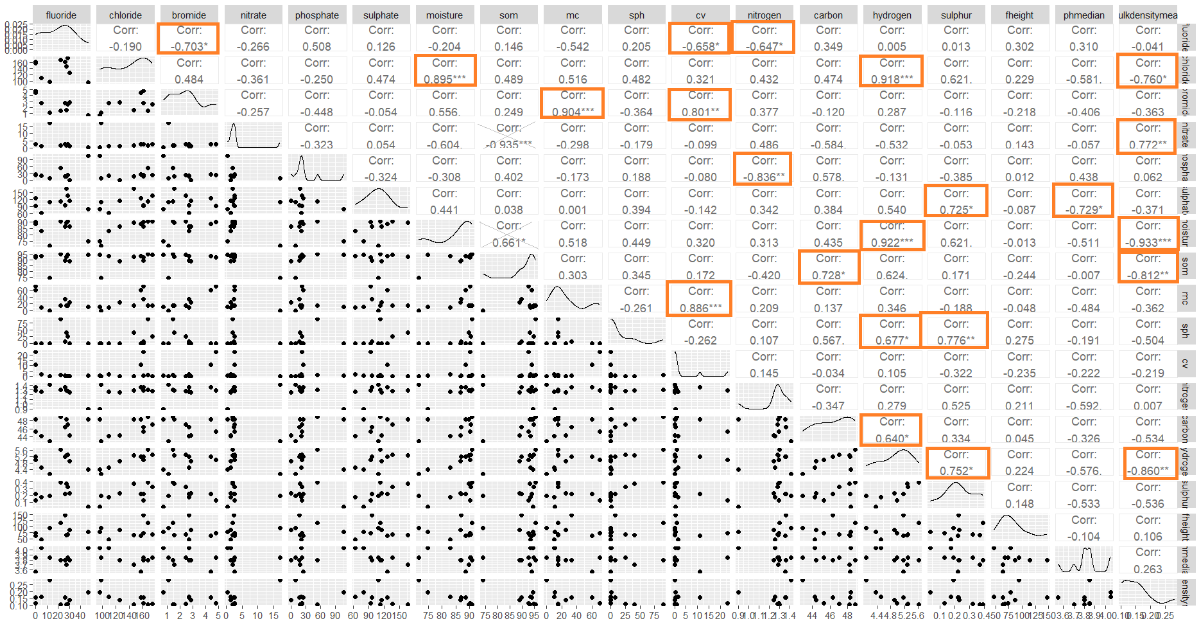

Figure 30: Correlation plots to visualise possible relationships between peat conditions and vegetation. Not all with high correlation coefficients are real effects.

A.6 Peat characteristic interactions

Table 6: Linear correlations showing the effect of peat variable 1 on peat variable 2.

Peat variable 1	**Peat variable 2**	**p-value**	β	$R^2_{multiple}$
Moisture	Bulk density	8.26×10^{-5}	-0.007418	0.87
Moisture	Chloride	0.000474	3.9619	0.8004
Moisture	Hydrogen	1.48×10^{-4}	0.0640	0.8499
Carbon	Hydrogen	0.0461	0.1442	0.4101
Carbon	SOM	0.01688	2.1906	0.5306
Chloride	Hydrogen	0.000181	0.014396	0.8422
Sulphur	Hydrogen	0.0122	3.3102	0.5652
Sulphur	Sulphate	0.01774	197.25	0.5252
Nitrogen	Fluoride	0.0338	-71.06	0.4499
Nitrogen	Phosphate	0.00474	-173.55	0.6518
Hydrogen	pH	0.04698	-0.20679	0.4076
Sulphate	pH	0.0124	-0.003931	0.5627

A.7 Raw vegetation survey data

Taxon/ cover type	Percent cover by quadrat by site																														Total by site		
	AC										AT										RT										AC	AT	RT
	1	2	3	4	5	6	7	8	11	12	9	10	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30			
	ac1	ac2	ac3	ac4	ac5	ac6	ac7	ac8	ac9	ac10	at1	at2	at3	at4	at5	at6	at7	at8	at9	at10	rt1	rt2	rt3	rt4	rt5	rt6	rt7	rt8	rt9	rt10			
Molinia caerulea	90	80	84	75	60	85	60	45	90	50	55	22	35	36	33	35	40	51	31	14	33	25	15	15		60	10	11	70	15	719	352	254
Betula																				2	2	0.5		0.5			2.5	1				2	6.5
Calluna vulgaris		28	1	10	20		3	40				13	4	7	7	2		1		2.5	0.5					11	1.5	0.5	23	1	102	36.5	37.5
Impatiens glandulifera																												0.5					0.5
Pteridium aquilinum																	5				0.5				80		0.5					5	81
Quercus								20																							20		
Unident. vascular plant																						0.5	0.5					0.5					1.5
Sphagnum cuspidatum																					8		25	40						90			163
Sphagnum fimbriatum				20	7																							0.5			27		0.5
Sphagnum papillosum																												0.5					0.5
Unident. *Sphagnum*																							5										5
Aulacomnium palustre							15																								15		
Campylopus introflexus													0.5		16					6	3						12	3.5				22.5	18.5
Hypnum jutlandicum		30	1		5						8	33	10	10	14	25	3.5	7.5	6	4						4.5		0.5	1		36	121	6
Unident. Hypnale moss																					19.5												19.5
Polytrichum commune			1	21	5		3						0.5						1	35			3.5	5	1			2			30	36.5	11.5
Polytrichum juniperinum															1																	1	
Unident. *Polytrichum*														0.5																		0.5	
Unident. Moss			2																												2		
Rickenella fibula						0.5																									0.5		
Unident. fungus																						0.5											0.5
Lichen																				2												2	
Stump algae																						0.5											0.5
Dead plant matter	75	50	35	10	40	40	25	33	65	45	37	20	35	22	25	13	38	45	40	10	3	3	1		85	15	6	1	15	2	418	285	131
Bare ground			7		33	15	15	20	5	25	20	5	25	16	15	8	17	15	18	5							50	5			120	144	55
Bog pool																					37	70	33	22		7			10	3			182
Woodchip																									40		9	32					81

Figure 31: Raw vegetation data showing percentage cover by quadrat and site.