MONITORING THE BIODIVERSITY AND ECOSYSTEM SERVICE IMPACTS OF RESTORATION OF DEGRADED BLANKET BOG SITES

CHAPTER 2: INTRODUCTION

MoorLIFE 2020

MoorLIFE 2020 Final Report:
Action D2

Monitoring the biodiversity and ecosystem service impacts of restoration of degraded blanket bog sites

Chapter 2: Introduction

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1. Summary

The MoorLIFE 2020 project area lies within the Peak District National Park and the South Pennines Moors Special Area of Conservation (SAC). The latter contains one third of the UK's Blanket bog habitat. This is a globally rare resource, with over 10% found in Britain alone. These areas play important roles in flood risk management, drinking water quality and carbon sequestration.

A long history of agricultural exploitation, commercial afforestation, outbreaks of wildfire, together with the effects of atmospheric pollution has led to degradation of these habitats. Keystone *Sphagnum* mosses disappeared, and extensive areas of bare peat were subject to deep erosional gullying. Apart from losing habitat and amenity value, these changes lead to substantially increased emissions of carbon dioxide, reservoir infilling and discoloration of water. In other areas, individual species have come to dominate large areas. These include hare's tail cottongrass (*Eriophorum vaginatum)*, common heather *(Calluna vulgaris)* and purple moor-grass *(Molinia caerulea)*.

Following nationwide flooding in the summer of 2007, the Pitt Review recommended the use of natural land management on upland headwater catchments to help mitigate flood risk, particularly in rural areas where there may be problems with the economics of conventional flood defences. Thus DEFRA provided grant funding in 2009 towards three projects under the Multi-Objective Flood Management Demonstration Scheme with the overall aim of generating hard evidence to demonstrate how integrated land management change, working with natural processes and partnership working can contribute to reducing local flood risk while producing wider benefits for the environment and communities. The Making Space for Water project was funded as one of three projects under this scheme, and concluded in 2015. The project found that bare peat restoration led to a range of important benefits to ecosystem services, including the potential to reduce the severity of flooding further downstream by delaying and reducing streamflow in the headwaters.

The monitoring work completed through this project was continued and broadened through the MoorLIFE 2020 project. Monitoring work continued at the original Making Space for Water sites to evidence the longer-term impacts of bare peat restoration, and three additional sites were set up using the same experimental design, to evidence the impacts of restoration on sites dominated by individual species: *Eriophorum*, *Calluna* and *Molinia*.

1.1. Bare Peat

The Making Space for Water project area was located on the north edge of Kinder Scout, within the upper Ashop catchment, a headwater catchment of the Upper Derwent valley. The 84-hectare project area was in one of the most severely degraded blanket bog habitats in the Dark Peak and South Pennines and probably the most severely degraded upland Blanket bog anywhere. It has an average height of 600 m and, in 2009, contained approximately 34% (28 ha) severely gullied and bare peat areas. The experimental design included thee mini-catchments of less than 1 ha, one of which would remain as an untreated bare peat control, one would be re-vegetated and one re-vegetated, gullies blocked and *Sphagnum* mosses planted. Pre-restoration and post-restoration monitoring took place on these three mini-catchments to support a "Before-After-Control-Impact" (BACI) design. An additional reference mini-catchment on the neighbouring Bleaklow plateau was located on a site considered to be representative of an intact Blanket bog.

The initial restoration process, completed through the Making Space for Water project (2011-2013) involved grazing exclusion and gully-blocking, followed by stabilisation of the bare peat using heather brash and seeding with amenity grasses, local grasses and dwarf shrubs. This was accompanied by an initial treatment with lime and fertiliser (nitrogen, phosphorus and potassium) followed by two more annual treatments of lime and fertiliser.

Plug plants of moorland species were also planted on scattered locations within the project area.

The project assessed the impacts of bare peat restoration on a range of ecosystem services associated with blanket bogs within the first four years following restoration.

These impacts included:

- 88% reduction in bare peat area, replaced by a vegetation community containing grasses, mosses and moorland shrubs
- Higher water tables (up to 38% closer to the surface)
- Delayed (up to 267%) and reduced (up to 37%) peak discharge during storm events, with the potential to reduce severity of flooding further downstream
- Over 90% reduction in erosion and fluvial transport of particulate organic matter (and therefore carbon)
- Short-term significant perturbation to carbon cycling following application of lime, seed and fertiliser
- Short-term reduction in water colour and dissolved organic carbon, but no significant longer-term changes

In 2015, once the initial phase of restoration had created suitable conditions for *Sphagnum* mosses to grow, a mixture of 11 *Sphagnum* species were planted across the project area (funded by the Peatland Restoration Project), including in one of the experimental mini-catchments. Additional *Sphagnum* was planted in targeted areas in this same mini-catchment in 2018 (funded by MoorLIFE 2020).

1.2. Species dominated sites

In addition to the bare peat sites which continued to be monitored through the MoorLIFE 2020 project, three sites were added to measure the effects of introducing *Sphagnum mosses* in sites dominated by *Eriophorum vaginatum*, *Calluna vulgaris* and *Molinia caerulea*. This element of the project aimed to monitor the biodiversity and ecosystem service impacts at demonstration sites and against blanket bog restoration trajectories at other project sites, and specifically the effects of interventions on:

- Vegetation community composition
- Water table levels and characteristics
- Surface water runoff characteristics
- Catchment discharge characteristics
- Particulate Organic Carbon
- Dissolved Organic Carbon discharge
- Water colour

While sites were set up using identical methods at each vegetation type, the project was not designed to compare results between vegetation types, but rather to investigate the change in treatment and control plots within individual vegetation types.

The *Eriophorum* dominated site selected is located at Birchinlee Pastures on Alport Moor, to the north-west of bare peat sites. It is situated at an elevation of 490m and consists of an estimated 75–95% *Eriophorum* cover. The *Calluna* dominated site is located at Swain's Head on Howden Moor (south-west of the settlement of Langsett) at an elevation of 500m, consisting of an estimated 80–90% *Calluna* cover. The *Molinia* dominated site is located further north on Moss Moor, approximately equidistant between the towns of Huddersfield and Rochdale at an elevation of 385 to 475m. This site consists of an estimated 50% purple-moor grass cover, as the upper part of the site is a steep hillside on which this species cannot establish.

The experimental design included two mini-catchments of similar sizes on each site, one of which would remain as an untreated control; one would be treated with *Sphagnum* moss plug plants. In addition, the *Calluna* dominated site would contain a third mini-catchment with *Sphagnum* moss treatment and gully blocking. All three sites include three run-off plots in each mini-catchment, which have been intensively planted with *Sphagnum*. Pre-intervention and post-intervention monitoring took place on these mini-catchments to support a "Before-After-Control-Impact" (BACI) design.

2. Background to the Project

The South Pennine Moors, occupying a large area of the Peak District National Park and containing the MoorLIFE 2020 project areas is an internationally recognised SAC. It is particularly notable for containing one-third of the UK's Blanket Bog habitat; a system that is globally rare (Britain holds between 10 and 20 % of the entire global resource) and endowed with an assemblage of vegetation types that is internationally our most important (Lindsay *et al* 1988; Tallis 1995). However, it was not until the 1980s that an increasing recognition of the special biodiversity value associated with this habitat became more widely accepted. It was not until even more recently that the role of blanket bogs in catchment hydrology and water quality has also become a focus of research, particularly in the case of upland blanket bogs, which provide 70% of Britain's drinking water (Natural England, 2009). In addition, the part played globally by peatlands in carbon sequestration is now gaining increased attention. Billions of tonnes of carbon are locked up as semi-decomposed vegetation in the wet peat, amounting to about 30% of all global soil carbon (Vitt, 2008) and more than four times the amount of carbon stored in the equivalent area of tropical rainforest (Lindsay *et al*, 2019).

2.1. Damage to Blanket Bogs and consequences

In the UK the condition of blanket bogs, and peatlands generally has for a long time been in decline. Continuous exploitation since the eighteenth century involving peat extraction, agriculture (drainage, burning, grazing, fertilizers and reseeding), commercial afforestation (drainage, fertilizers) and development (roads, housing, mining, drainage) have all taken their toll. The more insidious effects of industrial and agricultural pollution are widely recognised as having a particularly damaging effect on community composition in general and on mosses (especially *Sphagnum* mosses) and lichens in particular (Brooks and Stoneman 1997). These atmospheric pollutants can lead to enrichment of nutrients and/or toxic deposition of heavy metals and other chemicals. In conditions of relatively low nutrient enrichment, changes in species abundances of *Sphagnum* mosses may occur, e.g. *S. medium* has been found to tolerate higher levels of nitrate than *S. imbricatum* and this may cause the former to outcompete the latter (Brooks and Stoneman 1997). Under conditions of more intense pollution such as that which occurred over the southern Pennines during the Industrial Revolution, the decimation in the number and abundance of *Sphagnum* species (Tallis 1964) is very strongly linked with the appearance of soot particles in peat cores (Conway 1954). The sulphate component of this deposition reached levels higher than has been found anywhere else in Britain or even in Europe (Skeffington *et al* 1997) and is thought to have had a major toxic effect on *Sphagnum* species (Ferguson *et al* 1984; Ferguson and Lee 1983).

On a global scale, there are approximately 500,000 km^2 of damaged or degraded peatlands, which emit an estimated 2 Gtons of CO_2 annually (Joosten, 2010). This represents about 17% of total anthropogenic land use sector Greenhouse Gas Emissions and 4% of total anthropogenic Greenhouse Gas emissions (IPCC, 2019). While the scale of these emissions poses a significant cause for concern in the context of a global climate change, it also presents an opportunity to reduce – and even reverse – these emissions, if restoration processes can result in degraded peatlands reverting from carbon sources back to carbon sinks.

2.1.1. Bare peat

Reversing the decline of severely degraded and denuded blanket bogs with large areas of bare peat presents special problems due to the seeming irreversibility of vegetation loss. In the southern Pennines, apart from the more general and devastating effects of pollution, the loss of vegetation and the subsequent exposure of bare peat in certain sites can also be traced back to local outbreaks of wildfire between 1947 and 1980, and at one site due to a particularly heavy rainfall event as far back as 1834 (Tallis, 1995). This inability of bare peat areas to be recolonised by vegetation has been blamed on various factors, including physical instability, chemical unsuitability, lack of propagules and, until recently, over-grazing by sheep (studies listed in Tallis 1995).

Apart from the obvious loss of habitat and amenity value, severe erosion of exposed peat, due to the action of rain, snow, ice, wind and drought imposes a threat to the supply and quality of drinking water as a result of reservoir infilling and discoloration of water. In the South Pennines, erosional gullying is particularly severe. The origins of this phenomenon, and the associated drying of peat due to falling water tables, have been relatively well studied and can be traced back to more than 4000 years BP, when it is thought that prehistoric forest clearing may have destabilised higher and flatter areas of the upland landscape. More recent gullying on lower altitude, sloping terrain is more strongly linked with the factors listed above.

Periodic incidences of climatically induced drying of peat have also occurred in Britain, and ended, from between 550 and 900 years ago to the present day, except in the southern Pennines, where dry conditions have prevailed for an exceptionally long period. This unusually long spell may have been triggered by Roman forest clearance with the effects of post-mediaeval sheep farming interacting with the effects of the climatic mediaeval dry phase. Whatever the precise cause, estimates in 2007 suggested that 8% of blanket bog in the southern Pennines was bare and eroding at rates of at least 2.5 cm annually (Evans and Warburton, 2007), although some amount of that area has since been revegetated and stabilised. Tallis (1995) concluded that the underlying hydrology of this region has been fundamentally altered, perhaps irreversibly.

While until relatively recently there was a lack of evidence regarding the reversibility of the impacts of this degradation, the Making Space for Water project found that restoration of bare peat led to multiple benefits to ecosystem services within four years of restoration. These included reduced erosion rates, increased biodiversity, raised water tables and attenuated streamflow during storm events – with modelling suggesting this could lead to reduced flood severity further downstream.

2.1.2. Species dominance

Increasing dominance by single vegetation species on blanket bog is also considered a potential threat to wildfire risk, carbon sequestration, water quality, flood risk, and biological diversity. Sites dominated by purple moor-grass (*Molinia caerulea),* common heather *(Calluna vulgaris)* hare's-tail cottongrass (*Eriophorum vaginatum*) are all present in the South Pennine Moors SAC and represent a threat to diversity and conservation.

Molinia is widespread and common in the South Pennine Moors. Evidence suggests that it may have been dominating areas since at least the Industrial Revolution (Chambers and McCarroll, 2015), and this dominance may be increasing. For example, the area dominated by *Molinia* on Berry Greave – a blanket bog site on the Marsden Moor Estate – doubled between 1988 and 2015 (Meade, 2015).

Such processes may lead to the exclusion or displacement of blanket bog species that are considered to indicate "favourable" condition. (JNCC 2009, Defra 2007). Increasing *Molinia* dominance is likely to exacerbate the loss of carbon from blanket bog peat stocks – either by reducing the rate or reversing the processes of peat formation (Jepson, 2015). However, more evidence for the overall effect of *Molinia* dominance on these processes, as well as others including water quality regulation and overland flow (Shepherd *et al*., 2013) would be desirable.

There is a strong link between the dominance of single species of fire adapted vegetation – such as *Molinia* and *Calluna* – and the risk of wildfires occurring in the UK. Intense fires, which move quickly through such stands of vegetation, regularly occur during dry weather when a source of ignition is present – often as a result of arson or out-of-control prescribed burns. (Glaves *et al*., 2020). The creation of a large amount of dry and dead matter by these species after the growth season means a high fuel load is often present during the winter and into spring, when fires can do much damage to wildlife as well as to the peat substrate itself.

There is evidence that the dominance of *Calluna* can lead to the drying of peat, and the promotion of sub-surface erosion through the formation of peat pipes (Lindsay, 2010). Drier conditions are sub-optimal for species which rely on the wetness of peatlands. Populations of insects such as crane flies and their predators (which includes many protected and/or declining wader species) are likely to decline in the long term as a result (Defra, 2021).

Furthermore, dominance of *Calluna* has been shown to be indirectly detrimental on the growth of *Sphagnum* mosses due to an increase in evapotranspiration and resultant lowered water table depth. There is evidence that overland flow travels more slowly over moorland where *Sphagnum* is present compared to other vegetation cover types including *Calluna* and *Eriophorum*. (Worrall *et al*., 2007; Lindsay, 2010; Holden *et al*., 2008 reviewed in Shephard *et al*., 2013). Therefore, dominance of a catchment by *Calluna* or *Eriophorum* could translate into an increased risk of downstream flooding, and a higher level of DOC in water from that catchment.

A study by Green *et al*., 2011 indicates that methane emissions from blanket bogs dominated by both *Calluna* and *Eriophorum vaginatum* may be larger than those from areas where *Sphagnum papillosum* is the dominant species. This suggests that areas where *Sphagnum* species are excluded could play a larger role in contributing to climate change than those where they are present. This effect is also expected to increase in warmer climates. (Shephard *et al*., 2013)

2.2. Restoration of Blanket Bogs and potential consequences

Peatland restoration has been shown to be both a viable and important tool for global climate mitigation and is included in United Nations Framework Convention on Climate Change (UNFCCC) mechanisms (Joosten, 2010). The International Union for the Conservation of Nature (IUCN) UK Peatland Strategy provides a briefing on the state of peatlands within the UK, including the impact of current management and use, and the benefits of restoration (IUCN, 2018). It is clear that restoration processes provide benefits that are commensurate with local, national and international initiatives and policy.

2.2.1. Increases in diversity

The current background deposition of key atmospheric pollutants onto blanket bog habitats has declined to a level which supports vegetation recovery and diversification. Sulphur dioxide pollution has fallen dramatically in the UK since the 1960s, allowing conditions which support the re-establishment of key species. The Making Space for Water project (Pilkington *et al*, 2015) found that, where areas of bare peat were revegetated, the bare peat area reduced by 90% in the first 4 years after restoration, replaced by a mixture of vegetation species, with the number and % cover of indicator species present increasing year on year. Notably, however, *Sphagnum* mosses did not re-establish themselves within any of the monitored areas. This finding was supported by monitoring at revegetated sites across the South Pennines (referred to in this report as Wider Context Sites), where *Sphagnum* did not develop any meaningful cover in quadrats, although it was observed in a small number of isolated patches in wet areas outside of quadrats (Maskill *et al*, 2015).

Sphagnum mosses are known to be key species in blanket bog plant communities. As well as supporting peat accumulation (and therefore carbon sequestration) (Noble *et al*, 2019), they have been shown to have benefits for water quality (Ritson *et al*, 2016) and flood mitigation (Holden *et al* 2008).

2.2.2. Hydrology

Moorland restoration has the potential to alleviate downstream flood risk, as suggested by hydraulic modelling studies within the Making Space for Water project (Milledge *et al*, 2015). Revegetation of bare peat areas, and the diversification of existing vegetation swards (in particular with *Sphagnum* mosses), in combination with the blocking of erosion gullies may lead to a delay in catchment discharge by increasing surface roughness, reducing overland flow velocities, increasing temporary storage of water on the peat surface and behind gully blocks, and reducing in-channel flow velocities. The Making Space for Water project found that peak stormflow was delayed by up to 267% at restored bare catchments, with peak discharge reduced by 37%.

The project also found that water tables rose by 35 mm following restoration of bare peat areas.

2.2.3. Reduction of erosion: protection of carbon stores and increases in carbon sequestration

Peatlands are world's largest terrestrial store of carbon, holding more than twice the carbon stored in all the planet's forests (Crouch and Chandler, 2021). Gregg *et al* (2021) estimated that eroding modified (bare peat) bogs emit ~12–13 tonnes of carbon dioxide per hectare per year. The Making Space for Water project found that restoration processes led to a cessation, or at least a significant reduction (97%), in the peat erosion rates from bare peat areas (Pilkington & Crouch, 2015), and consequent reduction in major losses of C annually (>100 tonnes km^{-2}, Evans *et al*, 2006). Losses of dissolved organic carbon to surface waters may also be reduced by restoration processes. In addition to avoided losses, revegetation work may lead to sequestration of carbon from the atmosphere as new peat starts to form.

3. The Project Area

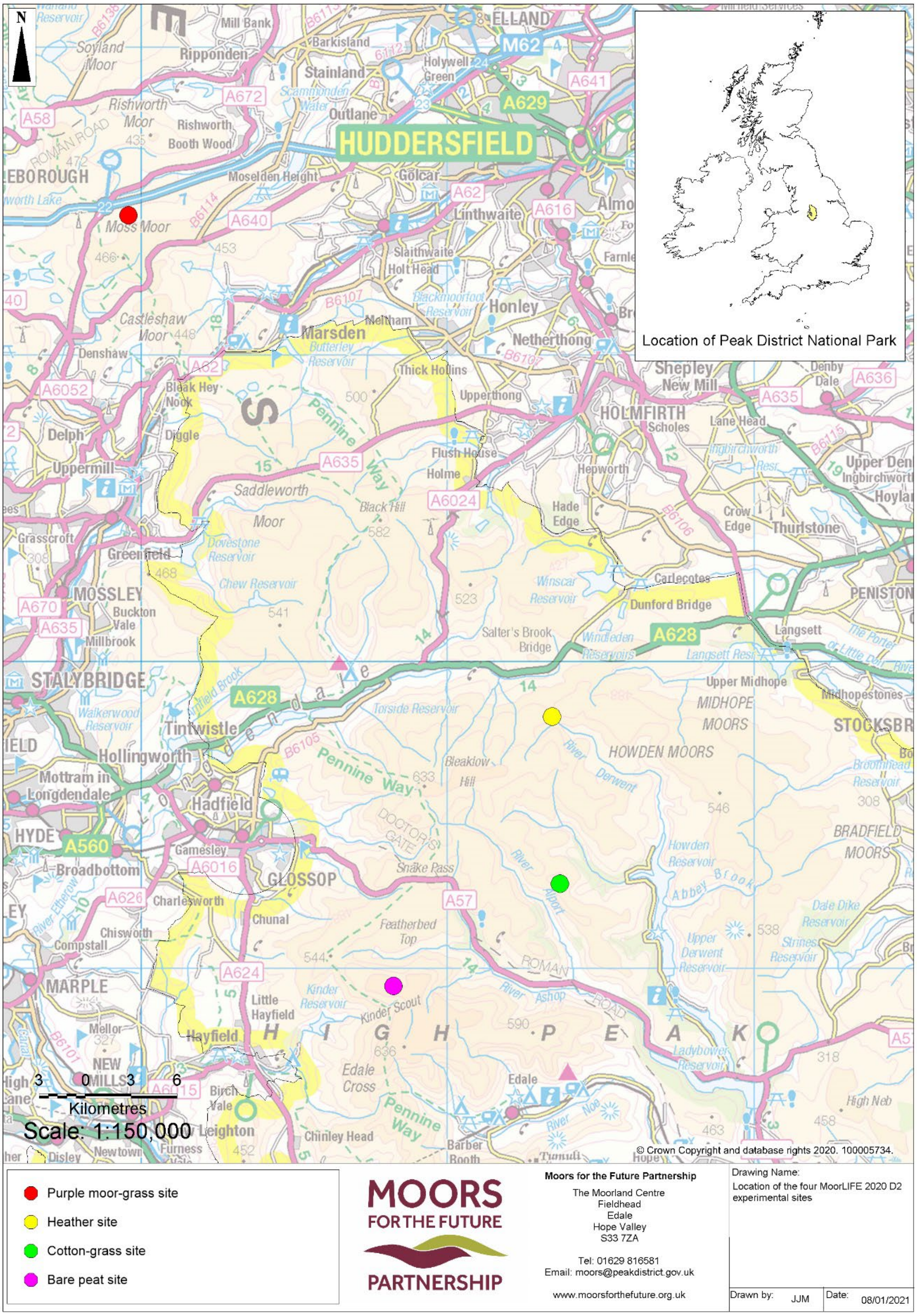

Figure 1: Locations of the four experimental sites within the ML2020 D2 project area

The four MoorLIFE 2020 D2 experimental sites are located within the South Pennine Moors SAC, and three of the sites are within the boundary of the Peak District National Park, see Figure 1. The two most northerly sites are located in West Yorkshire, and the two southerly sites are located in Derbyshire. The sites most distant from each other are the bare peat and *Molinia* dominated sites – approximately 26 km apart. All sites have a superficial deposit of deep peat (>40cm in depth).

3.1. Bare Peat

3.1.1. Location and description

The MoorLIFE 2020 Bare Peat (formerly the Making Space for Water) project area is situated on the north Edge of the Kinder Scout plateau within the Peak District National Park and between Manchester and Sheffield (Figure 2). Much of the the Peak District National Park is above 300 m, with the highest point on Kinder Scout at 636 m. The area is characterized by hills and gritstone escarpments ("edges"). The project area has approximate dimensions of 2000 m x 400 m, an area of approx. 84 ha and an average height of 600 m above sea level.

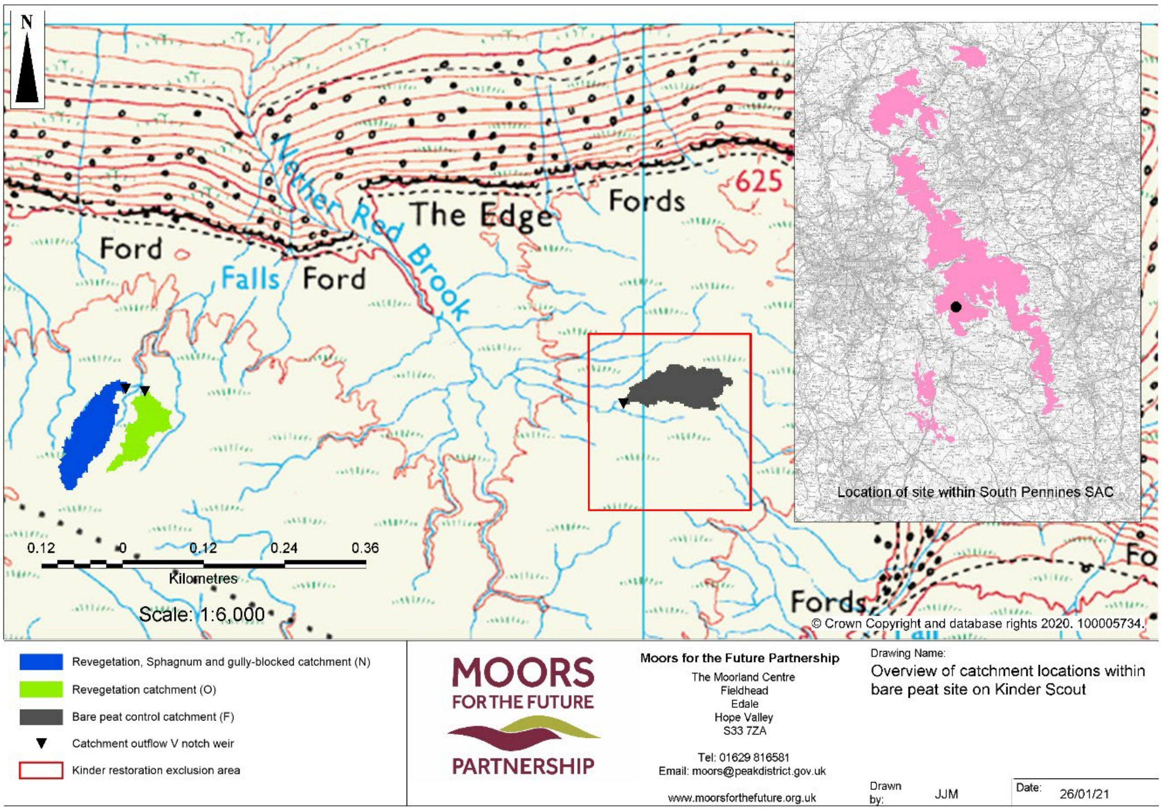

Figure 2: Bare peat project area

The project area encompasses an area of mainly undulating degraded blanket bog, often deeply gullied and with extensive areas which were bare peat until they were revegetated during the Making Space for Water project in 2011–12 (Figure 3). The project area was in one of the most severely degraded blanket bog habitats in the Dark Peak and South Pennines and probably the most severely degraded upland blanket bog anywhere.

Figure 3: Erosion gullies on Kinder Scout, untreated bare peat (left) and revegetated from bare peat (right, 11 years after initial treatment)

3.1.2. Bare peat area

The project area is located within the Upper Ashop Catchment (Figure 4) which leads downstream to the Derwent Catchment, where there have been relatively frequent historical flooding events.

Before the restoration activities began, and using landscape audit data from 2005, there was a dense concentration of bare peat in and around the project area – the 2817 ha of the upper Ashop catchment contained approximately 4% bare peat while the 84 ha Making Space for Water project area contained approximately 34% (28 ha) severely gullied and bare peat areas.

However, some three years or four growing seasons after the restoration had been fully completed, the area of bare peat had been drastically reduced from 28.4 ha in 2005 to 6.9 ha in 2014, representing a decrease of 75.6% in the area of bare peat over the whole of the Making Space for Water project area. As detailed elsewhere in this report, the revegetation work has resulted in comprehensive colonisation of the previously bare peat areas, with key 'indicator' species developing extensive cover within the vegetation community.

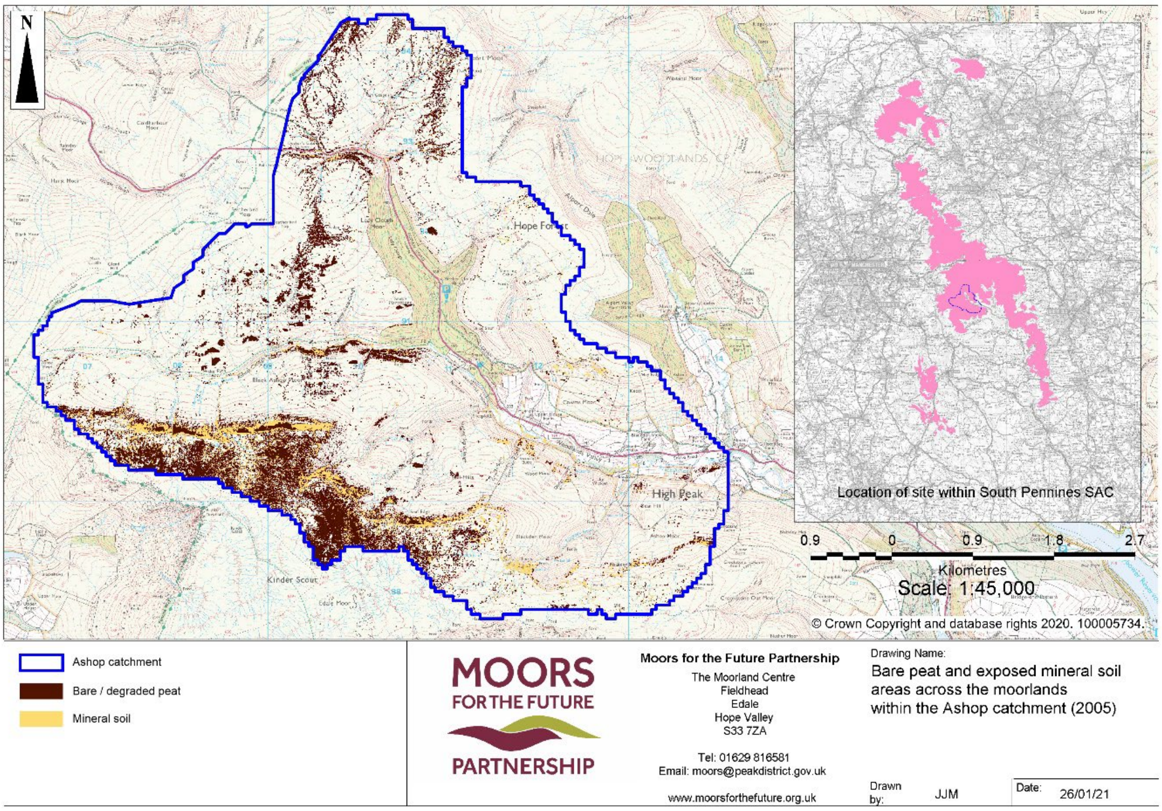

Figure 4: The extent of bare peat and exposed mineral soil at the start of the Making Space for Water project

3.2. Intact reference site ('Penguins')

An 'intact' site was selected to provide a context for the changes at the treatment sites over time. This site was selected to be as similar as possible to the bare peat experimental site on Kinder Scout in terms of location, elevation, catchment size and slope. Inevitably, it is significantly different in microtopography, vegetation cover and hydrological functioning as it has not been subject to the degradation and erosion which characterises the bare peat experimental site. The site is on Alport Moor, approximately 4 km north of the bare peat sites, at an elevation of 505 m above sea level (Figure 5). Its vegetation cover is dominated by grasses (*Eriophorum spp., Deschampsia flexuosa)* and there has been minimal historical erosion.

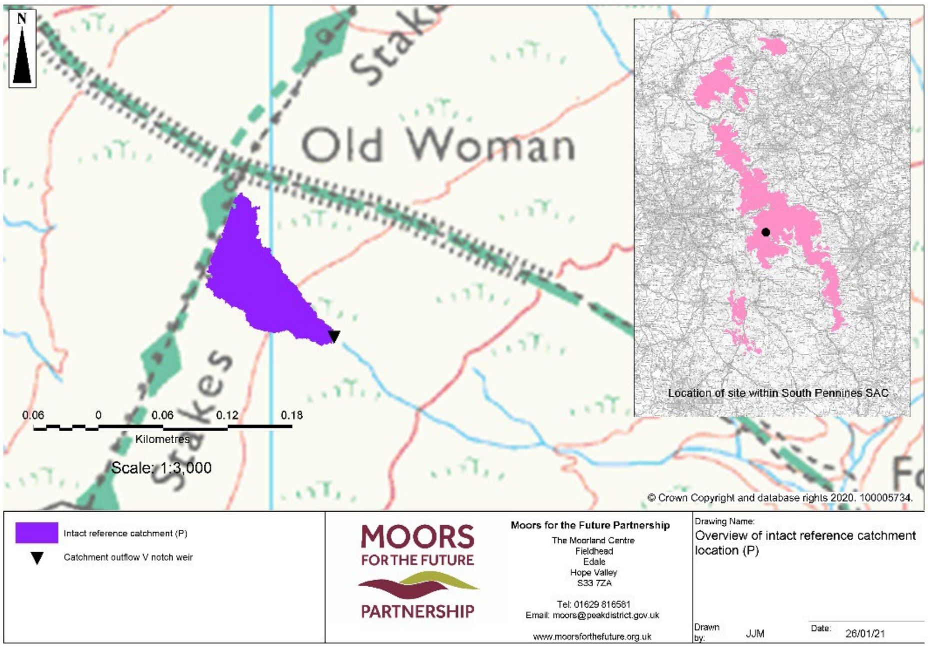

Figure 5. Location of intact reference site 'Penguins'

3.3. Species dominated sites

3.3.1. Locations and description

The MoorLIFE 2020 'species dominated' sites are situated in three locations. The *Calluna* and *Eriophorum* sites are both within the Peak District National Park, and the *Molinia* site is further north – outside the National Park boundary. All sites are within the South Pennines SAC (see Figure 1).

In contrast to the bare peat sites, the vegetation cover on these sites is largely intact and they have been selected primarily for their dominance by a single species of vegetation.

3.3.2. *Calluna* dominated area

The project area is situated at Swain's Head on Howden Moor, West Yorkshire within the upper catchment of the River Derwent (Figure 6). It is approximately 10 kilometres north north east of the Bare Peat site. The site is owned by MoorLIFE 2020 project partner the National Trust and is within the boundary of the Peak District National Park. It is located less than 100 m from the county boundary with Derbyshire.

The site is at an elevation of approximately 500 m, and is characterised by largely continuous (80–90%) heather (*Calluna vulgaris*), covering a peat layer over gritstone bedrock. Other vegetation present includes cottongrass species (*Eriophorum spp*.), small amounts of bilberry (*Vaccinium myrtillus*) and crowberry (*Empetrum nigrum*). Several other species are also present but infrequent. The landscape visible from the site is open and treeless in all directions.

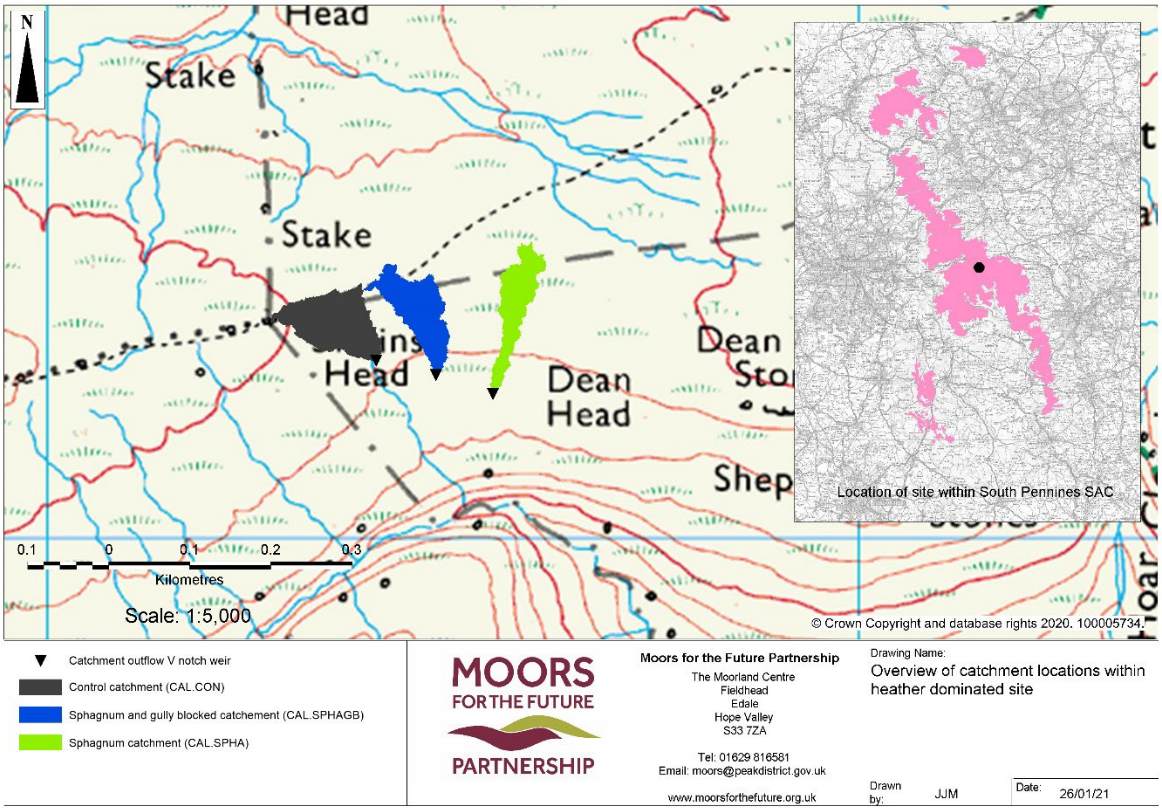

Figure 6: Overview of the *Calluna* dominated site

3.3.3. *Eriophorum* dominated area

The project area is situated at Birchinlee Pastures on Alport Moor, Derbyshire – approximately six kilometres northeast of the Bare Peat site (Figure 7). The site is owned by MoorLIFE 2020 project partner the National Trust and is within the boundary of the Peak District National Park. The two experimental mini-catchments within the area are situated along a watershed and drain into different river basins. The control mini-catchment drains to the west into the Westend catchment – a tributary of the River Derwent. The treatment mini-catchment inoculated with *Sphagnum* drains into the Alport catchment to the east.

The site has an elevation of approximately 490 m, and consist of an estimated 75–95% *Eriophorum* cover. The bedrock is in the Hebden mudstone/siltstone range, covered in a peat layer and adjoining shale grit/sandstone edges. Other vegetation present includes cross-leaved heath (*Erica tetralix*), common heather (*Calluna vulgaris*), wavy hair grass (*Deschampsia flexuosa*), deer grass (*Trichophorum germanicum*) and bilberry (*Vaccinium myrtillus*). Other species are also present but infrequent. The landscape is open and treeless in character.

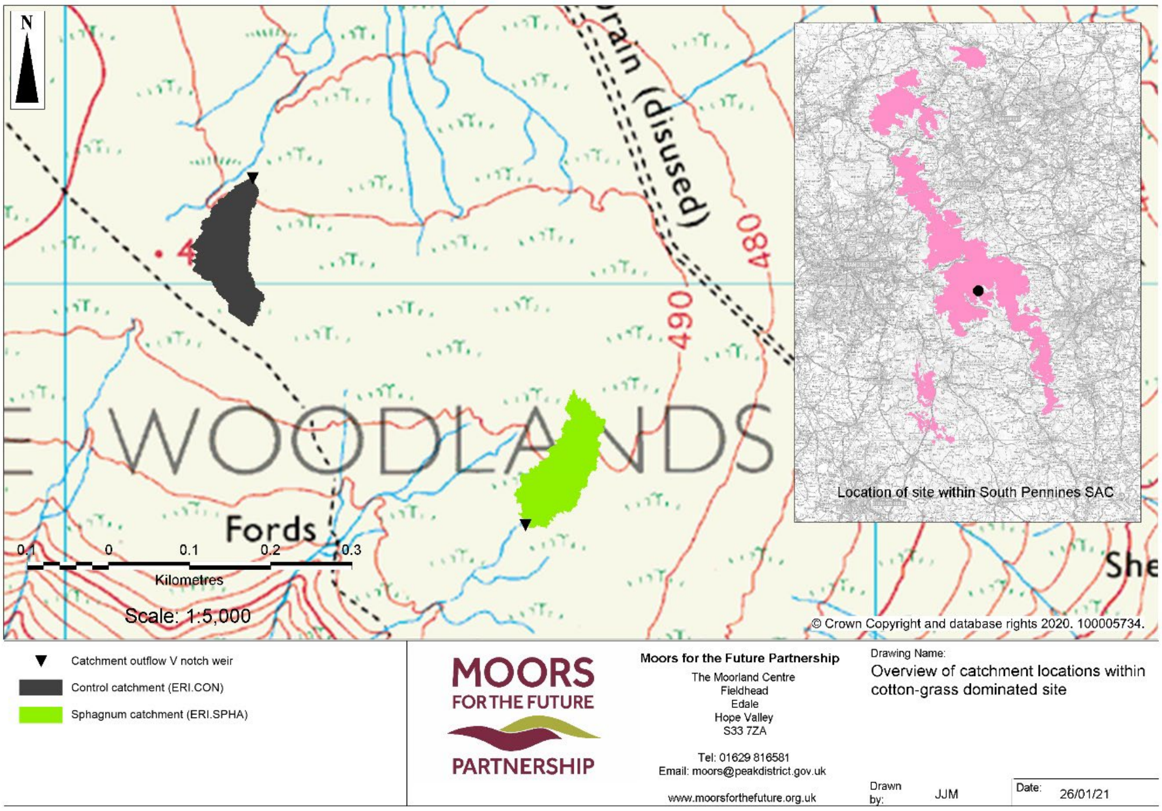

Figure 7: Overview of *Eriophorum* dominated site

3.3.4. *Molinia* dominated area

The project area is located on Moss Moor, West Yorkshire (Figure 8). It is approximately equidistant between the towns of Huddersfield and Rochdale, and around 26 km north of the bare peat site. The site is owned by MoorLIFE 2020 partner Yorkshire Water, and is within the Booth Dean Clough catchment, draining into the River Ryber.

The site elevation varies from 385 to 475m between the lower and upper limits of the mini-catchments selected. This site consists of an estimated 50% purple-moor grass cover overall, as the upper part of the site is a steep hillside on which this species cannot establish. The lower part of the catchment is densely covered with 90+% *Molinia*. The bedrock is gritstone and sandstone overlaid with a layer of peat. Other species present include small amounts of crowberry (*Empetrum nigrum*), bilberry (*Vaccinium myrtillus*), hare's-tail cottongrass (*Eriophorum vaginatum*) and wavy hair grass (*Deschampsia flexuosa*). The site is open, treeless in character, and situated within 400 metres of the M62 motorway.

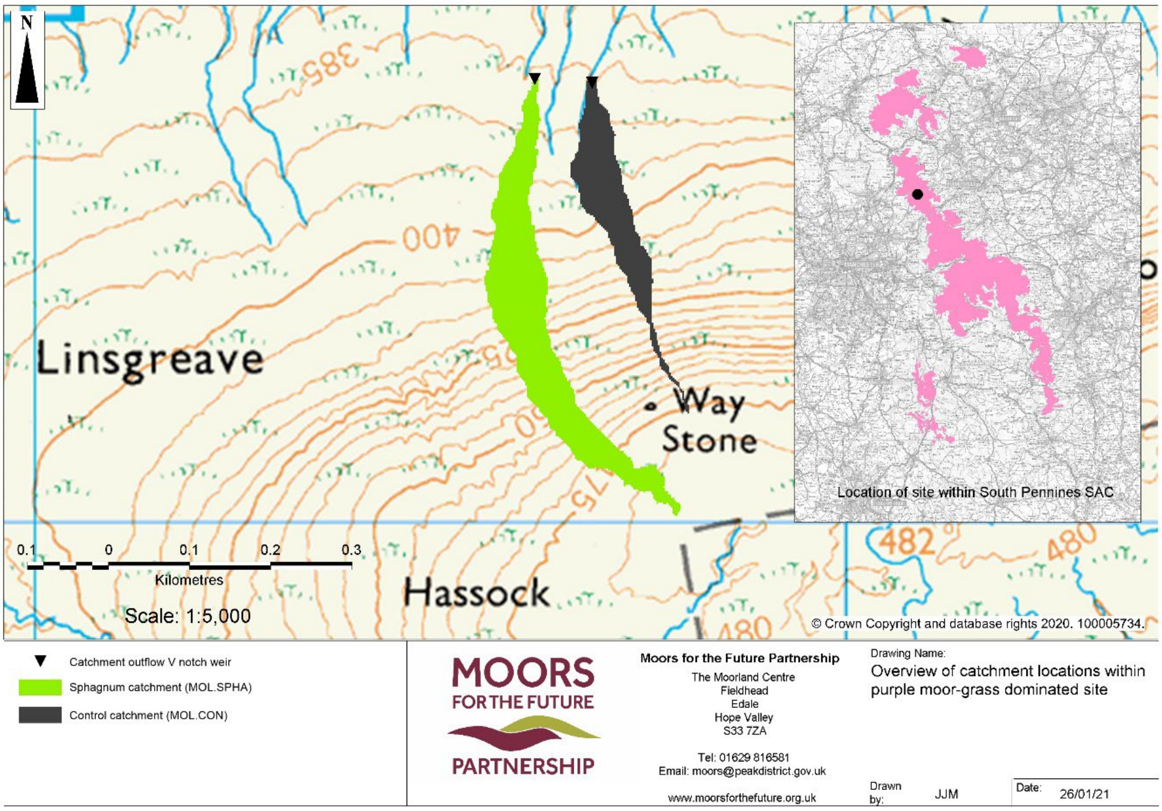

Figure 8: Overview of *Molinia* dominated site

4. The Restoration Process

The restoration methods used at each site are described in the following sections, and summarised in Table 8.

4.1. Bare Peat

The initial phase of restoration at the bare peat sites was completed under the Making Space for Water project in 2011–2013 and included grazing exclusion, gully-blocking, bare peat stabilisation (heather brash, geo-jute) and revegetation (seeding of amenity grasses and moorland species, with repeated applications of lime and fertiliser; planting of plug plants of moorland species). In 2015 and 2018, *Sphagnum* was planted in the form of mixed-species plug plants, including 11 different species of *Sphagnum*.

4.1.1. Grazing exclusion

Encircling the whole Kinder plateau, the stock exclusion fence (Figure 9) included the Making Space for Water project area and was completed in 2013 under the direction of the National Trust.

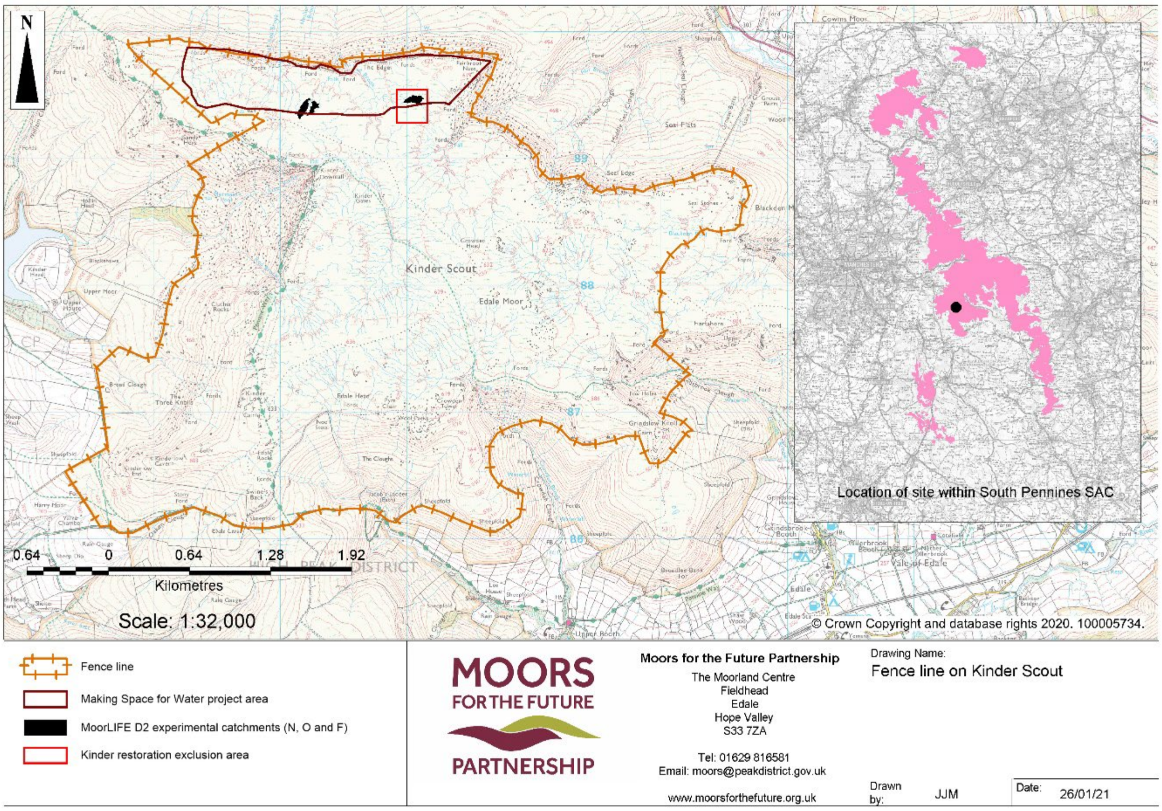

Figure 9: Grazing by sheep was excluded by the installation of a fence encircling the entire Kinder plateau, completed in 2013

4.1.2. Gully blocking

4.1.2.1. Installation

Approximately 2,100 dams were installed in gullies across the Making Space for Water project area in 2011/12, with an additional 100 dams installed at the western end of the project area in 2013. Within the experimental catchments, 26 dams (a combination of stone and timber) were installed in N (Figure 10); no dams were installed in O or F.

Stone dams were used mainly on gullies with a mineral base or a relatively shallow (less than 50 cm and preferably firm and static) peat base. The dams were built using millstone grit pieces of 75–200 mm diameter. Where possible, each dam was located so that the pond received water directly from the upstream dam and was also shaped to have a longer downstream run-off slope and a central depression to promote flow over the centre of the dam.

Timber dams were used mainly on gullies with deeper peat (more than 50 cm) and peat that was more mobile. Timber dams were constructed using 5–6 fencing boards of Western Red Cedar and 2 squared fencing stakes. Each dam was located so that the pond received water directly from the upstream dam and was also equipped with a 38 mm deep notch cut into the top board of each dam to promote flow over the centre of the dam. Stones were placed at the base of each dam to minimise the risk of undercutting.

No additional dams were installed within the project area through MoorLIFE 2020.

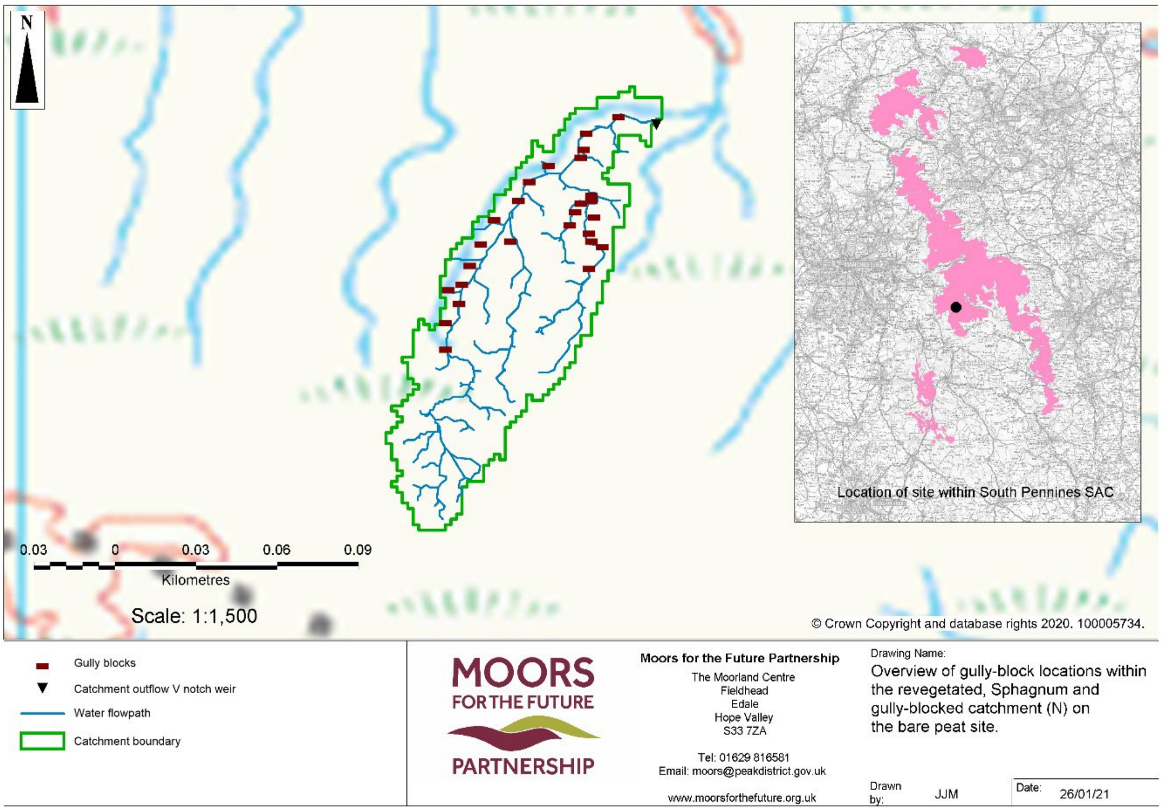

Figure 10: Gully block locations within the N catchment on the bare peat site

4.1.2.2. Maturation of gully blocks

In the years following installation, the condition of the gully blocks has changed in a variety of ways. As peat eroded from areas of bare peat (predominantly in the first year following installation, as erosion rates decreased significantly with the establishment of vegetation cover) and bare gully walls, it was transported through the stream network, bringing it into contact with the gully blocks. Stone dams in particular (and timber dams to a lesser extent) tend to trap sediment, both within the dam structure itself, and within the channel in the area immediately upstream of the dam. At some dams, sediment deposits have built up almost to the height of the top of the dam; at others, almost no sediment deposit is evident. This variability is most likely a result of variability in the availability of a sediment source in the contributing area of each dam, in combination with the number and sediment-trapping efficacy of the dams upstream of the dam in question.

These sediment deposits tend to be well-vegetated, as seeds (from initial application in 2011 and produced by local vegetation) wash down into the streams, accumulate there and then germinate and grow. As with the extent of sedimentation, extent of vegetation cover on and around the dams is variable. Some dams are now entirely invisible due to the extent and density of vegetation that has established over them; some have little or no vegetation cover at all.

Some of the dams hold water in pools immediately upstream of the dam for most of the year, drying up only in prolonged periods of no rainfall; others drain out after only a few days of no rain. In general, the timber dams tend to hold water for longer and the stone dams for less time, but where the stone dams have infilled with sediment and vegetated over they often maintain pools for extensive periods (see Figure 11).

Figure 11: Gully blocks at mini-catchment N in varying states of maturation (February 2022)
a) stone blocks partially sedimented, creating semi-permeable dam with temporary water storage capacity; b) stone blocks fully sedimented, creating minimally-permeable dam with long-term pool and minimal available temporary storage capacity; c) timber dams with gaps between planks partially sedimented, creating semi-permeable dam with temporary water storage capacity; d) timber dams with gaps between planks fully sedimented, creating minimally-permeable dam with long-term pool (full of Sphagnum) and minimal available temporary storage capacity

4.1.3. Heather brash

Heather brash was spread over the bare peat areas in the Making Space for Water project in 2011 (Figure 12), including mini-catchments O and N. A 200 x 200 m exclusion area was left without brash, including the bare peat control mini-catchment (F). No additional heather brash has been applied within the project area through MoorLIFE 2020.

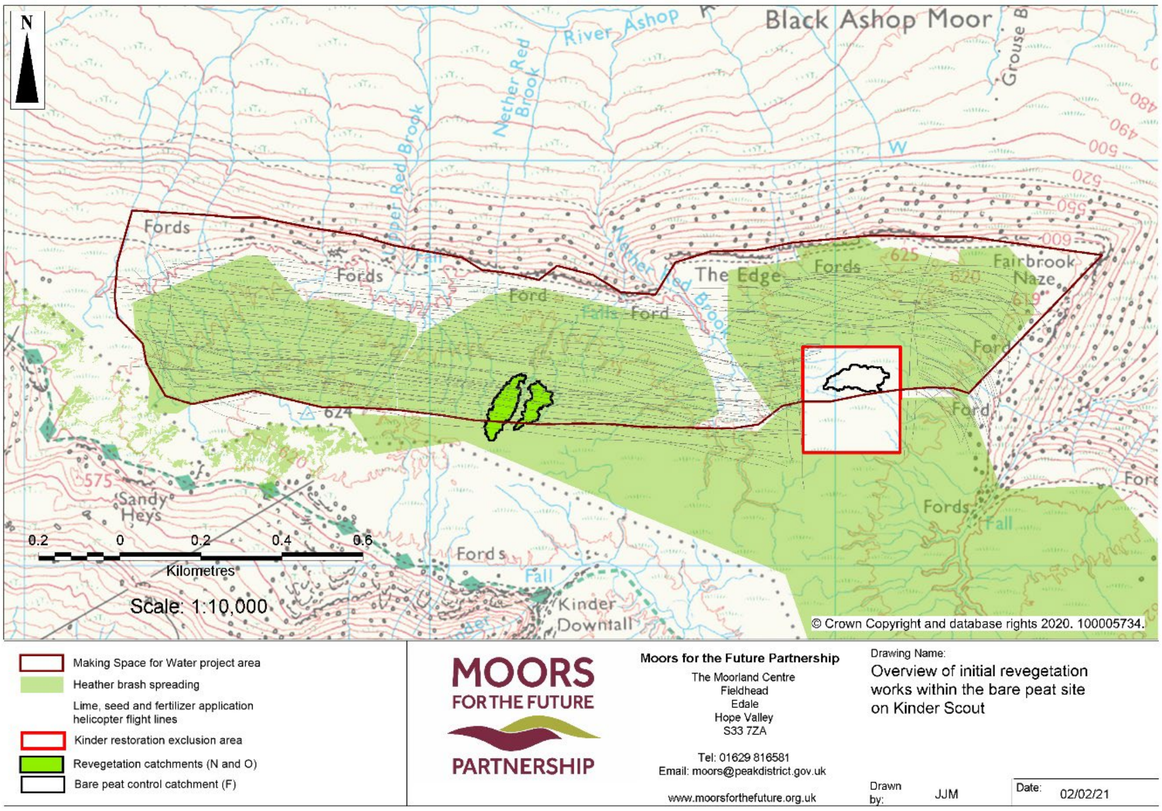

Figure 12: Heather brash and lime, seed and fertilizer treatments within the bare peat area

4.1.4. Lime and fertiliser treatments

Lime and fertiliser were applied using a helicopter-suspended hopper over the whole of the Making Space for Water project area, including mini-catchments O and N (see rates of application in Table 1 and map in Figure 12). The 200 x 200 m exclusion area containing the bare peat control mini-catchment (F) received no lime or fertiliser.

Table 1. Application rates of lime and fertiliser across the Making Space for Water project area

	2011	2012	2013
Lime	1000kg ha^{-1} of 98% $CaCO_3$, 0.5% $MgCO_3$ and 1% Si_2	1000kg ha^{-1} of 98% $CaCO_3$, 0.5% $MgCO_3$ and 1% Si_2	1000kg ha^{-1} of 98% $CaCO_3$, 0.5% $MgCO_3$ and 1% Si_2
Fertiliser	361 kg ha^{-1} of 40 N: 120 P_2O_5: 60 K_2O	278 kg ha^{-1} of 40 N: 60 P_2O_5: 60 K_2O	278 kg ha^{-1} of 40 N: 60 P_2O_5: 60 K_2O

The fertiliser supplier quoted the resulting ratio N:P:K as being N 11: P 33.5: K 16 (initial) and N 14.5: P 21.5: K 21.5 (maintenance). No additional lime or fertiliser has been applied within the project area through MoorLIFE 2020.

4.1.5. Treatment with seeds of amenity grasses, local grasses and dwarf shrubs

Seeds were applied using a helicopter-suspended hopper over the whole of the Making Space for Water project area, including mini-catchments O and N (see map in Figure 12).

The 200 x 200 m exclusion area containing the bare peat control mini-catchment (F) received no seed application. A single treatment of seed was applied in July 2011:

(i) Amenity grasses (49 kg ha^{-1})
  a. Perennial rye grass (*Lolium perenne*) (3 varieties)
  b. Sheep's fescue (*Festuca ovina*)
  c. Hard fescue (*Festuca ovina* var. *duriuscula*)
  d. Highland bent (*Agrostis castellana*);

(ii) Locally collected grass (1 kg ha^{-1})
  a. Wavy hair grass (*Deschampsia flexuosa*)

(iii) Dwarf shrubs (0.65 kg ha^{-1})
  a. Heather (*Calluna vulgaris*)
  b. Cross-leaved heath (*Erica tetralix*)

No additional seed has been applied within the project area through MoorLIFE 2020.

4.1.6. Moorland indicator species plug plants

38,000 plug plants were planted across the whole of the Making Space for Water project area, including mini-catchments O and N (see map in Figure 12). The 200 x 200 m exclusion area containing the bare peat control mini-catchment (F) received no plug plants. Each plug contained a single vascular plant (all indicator species) with the following proportions of species:

Common Cotton Grass (*Eriophorum angustifolium*)	50%
Crowberry (*Empetrum nigrum*)	19%
Bilberry (*Vaccinium myrtillus*)	14%
Hare's Tail Cotton Grass (*Eriophorum vaginatum*)	13.5%
Cloudberry (*Rubus chaemaemorus*)	2%
Cross Leaved Heath (*Erica tetralix*)	1.5%

No additional vascular species plug plants have been planted within the project area through MoorLIFE 2020.

4.1.7. *Sphagnum*

Sphagnum mosses were planted as plug plants into mini-catchment N in two phases: catchment-wide planting in March 2015 and in flow pathways in March 2018. These two planting phases combined resulted in a total of 53,550 plugs being planted across the ~0.7Ha mini-catchment, at an average density of 8 plugs per m^2.

4.1.7.1. Catchment-wide planting

Sphagnum mosses were planted throughout mini-catchment N in March 2015, through the Peatland Restoration Project. 11 *Sphagnum* species were planted in the form of mixed-species plug plants, supplied by Micropropagation Services Ltd. Each plug contained a mix of all 11 species in the proportions listed in Table 2 (the proportions listed are estimated averages from the supplier). 36,550 plugs were planted in the mini-catchment, with planting focused in optimum mini-topographic locations, but including on hag tops where there were slight depressions. Across the catchment as a whole this resulted in an average plug density of ~5 per m^2.

4.1.7.2. Planting in flow pathways

An additional 17,000 plugs were planted in late March 2018. The plugs contained the same 11 species and in the same proportions as for the catchment-wide planting in 2015. Planting was focused on flow pathways throughout mini-catchment N, with the intention of bringing as much streamflow as possible into contact with *Sphagnum*, in particular during storm events. Where there was already good coverage in the flow pathways, plugs were planted at the margins – in areas which would only be in contact with streamflow in large flow events. Along all of the combined flow pathways this resulted in an average plug density of ~34 per m^2.

Table 2. *Sphagnum* species proportions in plugs planted in mini-catchment N

Species	% of total mix
Fallax	25%
Palustre	24%
Papillosum	20%
Capillifolium	5%
Cuspidatum	10%
Fimbriatum	5%
Subnitens	5%
Denticulatum	3%
Squarrosum	2%
Tenellum	0.5%
Magellanicum (now Medium)	0.5%

Table 3. Planting density of *Sphagnum* plugs at mini-catchment N

	Area (m^2)	Average Density (m^{-2})	*Sphagnum* Plugs (Count)
Catchment-wide planting (2015)	6970	5	36,550
Flow pathways (2018)	500	34	17,000
Total	**6970**	**8**	**53,550**

4.2. Species dominated

4.2.1. Gully blocking

18 timber dams were installed in March 2019 in gullies within one of the treated mini-catchments on the *Calluna* dominated site (see locations in Figure 13). Dams were constructed each using 2–6 untreated timber boards and 2–4 squared fencing stakes. Each dam was located so that the pond received water directly from the upstream dam and was also equipped with a 200 mm wide x 50 mm deep notch cut into the top board to promote flow over the centre of the dam. Splash plates were installed below the notch to minimise the risk of undercutting through turbulence erosion.

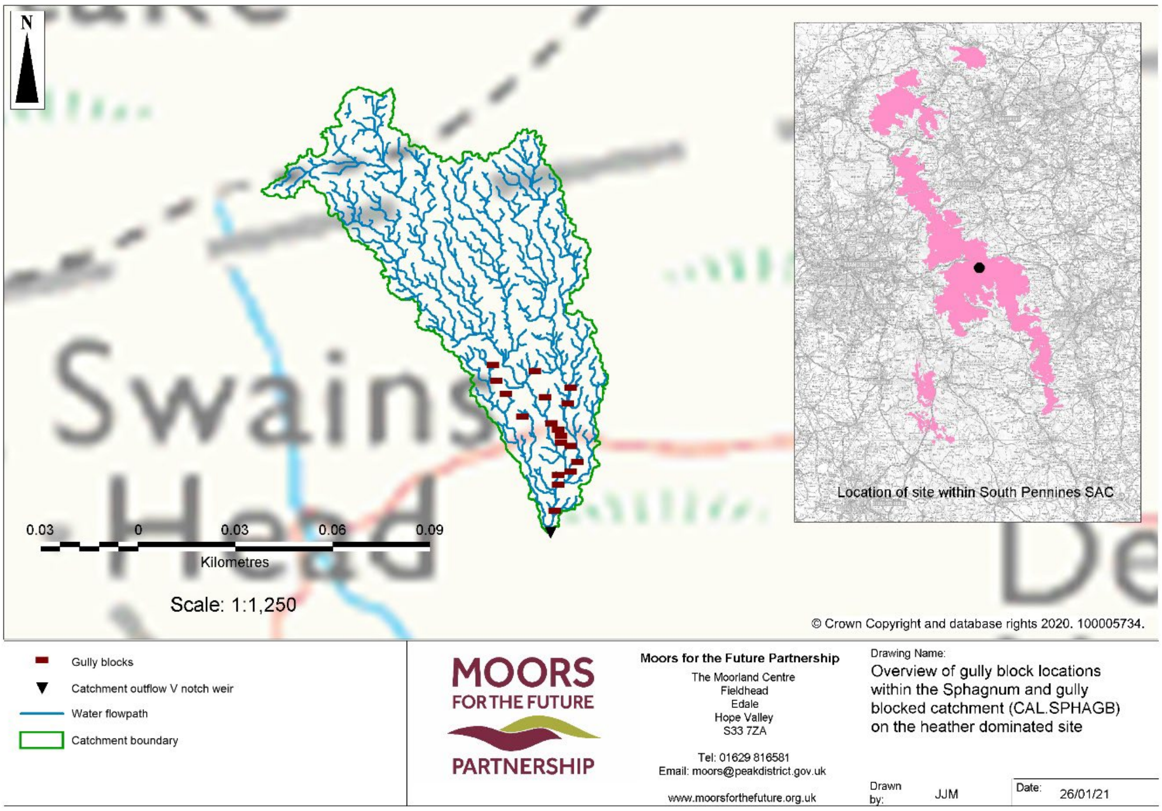

Figure 13: Gully block locations within the SphaGB catchment on the *Calluna* dominated site

4.2.2. *Sphagnum*

Sphagnum moss plug plants were introduced throughout relevant mini-catchments on each of the species dominated sites during March 2019 (intensive plots were planted slightly later in August/September 2019). 11 *Sphagnum* species were planted in the form of mixed-species plug plants, supplied by Micropropagation Services Ltd. Each plug contained a mix of all 11 species in the proportions listed in Table 2 (the proportions listed are estimated averages from the supplier).

The *Calluna* dominated site had 38,550 *Sphagnum* plugs planted (20,890 in the Cal.spha catchment and 17,660 in the Cal.sphaGB catchment). The *Eriophorum* dominated site had 25,070 plugs planted, and the *Molinia* site had 36,470 plugs planted (summarised in Table 4). Where possible, planting took place regularly in lines regardless of micro-topography or variations in vegetation.

Table 4. Species dominated catchment areas and total *Sphagnum* plugs planted

Site	Catchment	Catchment area (m^2)	Plugs planted
Calluna	Spha	4,900	20,890
	SphaGB	5,900	17,660
Eriophorum	Spha	12,100	25,070
Molinia	Spha	25,300	36,470

4.2.2.1. Catchment-wide planting

Sphagnum mosses were planted at density of 1 plug per m^2 across the catchments outside of the higher density areas outlined below.

4.2.2.2. Dipwell cluster planting
The 30 x 30 m area of each treatment catchment containing 15 dipwells, had *Sphagnum* plugs introduced at a higher density of 4 plugs per m^2. These were planted in March 2019, in geometric lines spaced at 50 cm apart, regardless of micro-topography or variations in vegetation.

4.2.2.3. Intensive plot planting
Each 3 x 1 metre intensive run-off plot area was planted with *Sphagnum* plugs at the highest density of 100 plugs per m^2. These were planted in August/September 2019, in geometric lines spaced at 10 cm apart, regardless of micro-topography or variations in vegetation.

4.2.2.4. Planting in flow pathways
A higher density of 4 plugs per m^2 were planted in the main gullies and flow paths of the treatment catchments. These were planted in March 2019 with a separation of 50 cm. Gully bottoms were avoided to reduce the risk of washing out during storms.

Table 5. Variables associated with planting plugs in the sections of the *Calluna* field laboratory

	Catchment area (m^2)	Section area (m^2)	Spacing (m)	Density (m^{-2})	*Sphagnum* Plugs (Count)
Catchment "Spha"					
Intensive plots	4,900	9	0.1	100	900
Dipwell cluster	4,900	900	0.5	4	3,600
Flow path (30%)	4,900	2730	0.5	4	10,920
Remainder	4,900	5470	1	1	5,470
Sub Total					**20,890**
Catchment "SphagGB"					
Intensive plots	5,900	9	0.1	100	900
Dipwell cluster	5,900	900	0.5	4	3,600
Flow path (30%)	5,900	2220	0.5	4	8,880
Remainder	5,900	4280	1	1	4,280
Sub Total					**17,660**
Total					**38,550**

Table 6. Variables associated with planting plugs in the sections of the *Eriophorum* field laboratory

	Catchment area (m^2)	Section area (m^2)	Spacing (m)	Density (m^{-2})	*Sphagnum* Plugs (Count)
Intensive plots	12,100	9	0.1	100	900
Dipwell cluster	12,100	900	0.5	4	3,600
Flowpath (30%)	12,100	3390	0.5	4	13,560
Remainder	12,100	7010	1	1	7,010
Total					**25,070**

Table 7. Variables associated with planting plugs in the sections of the *Molinia* field laboratory

	Catchment area (m^2)	Section area (m^2)	Spacing (m)	Density (m^{-2})	*Sphagnum* Plugs (Count)
Intensive plots	25,300	9	0.1	100	900
Dipwell cluster	25,300	900	0.5	4	3,600
Flowpath (30%)	25,300	5190	0.5	4	20,760
Remainder	25,300	11210	1	1	11,210
Total					**36,470**

4.3. Summary of interventions on all catchments

Table 8. Restoration methods used at ML2020 sites

Restoration process	Bare Peat sites				*Calluna* site			*Eriophorum* site		*Molinia* site	
	F	P	O	N	Cal.Con	Cal.Sph	Cal.SphaGB	Eri.Con	Eri.Spha	Mol.Con	Mol.Spha
Grazing exclusion	2013	-	2013	2013	-	-	-	-	-	-	-
Gully blocking	-	-	-	2011	-	-	2019	-	-	-	-
Heather brash	-	-	2011	2011	-	-	-	-	-	-	-
Geo-jute	-	-	2011	2011	-	-	-	-	-	-	-
Seeding: amenity grasses and moorland species	-	-	2011	2011	-	-	-	-	-	-	-
Lime + fertiliser	-	-	2011 2012 2013	2011 2012 2013	-	-	-	-	-	-	-
Sphagnum planting	-	-	-	2015 2018	-	2019	2019	-	2019	-	2019

5. Monitoring Design

Pre-restoration and post-restoration monitoring took place at restored and untreated control mini-catchments at all four sites to support a "Before-After-Control-Impact" (BACI) design at each site. At two of the sites (bare peat and *Calluna*-dominated), two different restoration packages were trialled at separate mini-catchments, in addition to the untreated control catchments. Within each site, the mini-catchments included in the monitoring programme were selected to be as similar as possible to each other in terms of size, gradient, aspect, topography and pre-restoration condition.

Table 9. Mini-catchments included in monitoring design at the four MoorLIFE 2020 project sites

Site starting condition	Untreated control catchment	Revegetation catchment	Revegetation, gully-blocking, *Sphagnum* planting catchment	Gully-blocking, *Sphagnum* planting catchment	*Sphagnum* planting catchment
Bare Peat	✓ *	✓	✓		
Calluna-dominated	✓			✓	✓
Molinia-dominated	✓				✓
Eriophorum-dominated	✓				✓

*two untreated control catchments included: one bare peat and one 'intact' reference

An overview of the monitoring carried out through the MoorLIFE 2020 project is presented in the following sections and in Figure 14, Figure 13 and Table 11; further detail is included in the relevant sections of this report. The monitoring programme used at the bare peat site was designed and installed in the Making Space for Water project. The same design has been continued through MoorLIFE 2020, with a small number of additions. A similar design was used for the species dominated sites. Within each site, the mini-catchments were selected to be as similar in size as was practicable, to make them as comparable as possible.

5.1. Naming of the mini-catchments

The names given to each mini-catchment are listed in Table 10, with a summary of their associated restoration treatments.

Table 10. Names of mini-catchments, and summary of associated restoration treatments

Site/mini-catchment name		Treatment
Bare peat	F	None (bare peat control)
	P	None (intact reference)
	O	Revegetation
	N	Revegetation, gully blocking, *Sphagnum*
Common heather (*Calluna*)	Cal.Con	None (control)
	Cal.Spha	*Sphagnum*
	Cal.SphaGB	*Sphagnum*, gully blocking
Cottongrass (*Eriophorum*)	Eri.Con	None (control)
	Eri.Spha	*Sphagnum*
Purple moor-grass (*Molinia*)	Mol.Con	None (control)
	Mol.Spha	*Sphagnum*

5.2. Vegetation diversity

A series of 2 x 2 m quadrat locations were selected at random within each of the 11 mini-catchments. At each of these locations, annual summer surveys have recorded percentage cover of every vegetation species present. Due to the difficulties of identifying *Sphagnum* mosses to species level in the first years after planting as mixed-species plugs, all *Sphagna* were simply recorded as total *Sphagnum* cover at the species dominated sites. At the bare peat site, where *Sphagnum* was planted in 2015 in one of the mini-catchments, *Sphagnum* was recorded to individual species level in surveys in 2018 and 2020.

Repeat fixed point photos were taken at all four mini-catchments where *Sphagnum* plugs were planted, to assess the growth of the plugs.

5.3. Hydrology

The boundary of each of the 11 mini-catchments was defined by the location and installation of a v-notch weir. These weirs were instrumented with electronic water height sensors for the continuous quantification of streamflow discharge from each catchment. They also provided suitable locations for the collection of water samples for water chemistry analysis.

Rainfall input to each mini-catchment was monitored using a rain gauge with tipping bucket, allowing the continuous quantification and timing of rainfall intensity during rain events.

Within each mini-catchment water tables were monitored both continuously (using water height sensors) and through manual survey campaigns of clusters of 15 randomly located dipwells. The manual surveys comprised weekly readings at all dipwells for a 12-week period each autumn. For the rest of the year, three-weekly readings were taken from all dipwells at the species dominated sites. The sensors provide high temporal resolution; the manual dipwell clusters provide high spatial resolution.

The generation of overland flow was monitored using crest stage tubes. At the bare peat sites these were monitored through manual survey campaigns of clusters of 9 tubes. At the species-dominated sites, these were located adjacent to each manual dipwell and were monitored every three weeks. Overland flow was also monitored on the species dominated sites using run-off plots, which direct rain falling on a fixed surface area though guttering and pipe to a rain gauge with tipping bucket, allowing for high temporal resolution recording of surface run-off.

Sub-surface water was also monitored at the species dominated sites using piezometers installed at 5 cm and 10 cm depths – located adjacent to manual dipwells and crest stage tubes.

5.4. Water Chemistry

Water chemistry was monitored at all 11 mini-catchments, as detailed below.

5.4.1. Bare Peat

Sets of 3 samples were collected from streamflow at the v-notch weir at each catchment once per fortnight using 30ml screwcap Universal tubes. Each tube was rinsed 3 times with streamwater before the sample was collected. The samples were stored in an opaque bag (an insulated bag was used during warm weather) while in the field and then stored in a fridge until analysis.

At the laboratory, samples were filtered at 0.45 microns. From 2011–2014, samples were analysed colorimetrically using a Hach spectrophotometer. Absorbance was measured at 254 nm, 400 nm, 465 nm and 665 nm; absorbance at 400 nm was used as a proxy for DOC in 2011. From 2012 onwards DOC was also measured directly, as non-purgeable organic carbon (NPOC) via UV-persulphate oxidation on a Shimadzu TOC analyser. Water chemistry was analysed by ICP-OES and Ion chromatography to provide contextual data.

5.4.2. Species Dominated

Samples were collected from the species dominated site on a three-weekly basis. A set of seven samples were collected from each mini-catchment covering:

- Water from crest stage tubes in the 'cluster'
- Water from the 5 cm piezometers in the 'cluster'
- Water from the 10 cm piezometers in the 'cluster'
- Water from the crest stage tubes in the intensive plots
- Water from the 5 cm piezometers in the intensive plots
- Water from the 10 cm piezometers in the intensive plots
- Water from the V-notch weir outflow

For each sample type excluding the weir outflow, water was taken in equal proportions from multiple locations within the mini-catchment. For example, 3 ml was taken from every crest stage tube within the cluster of 15, and combined as a 45 ml sample to represent that catchment.

Samples were extracted from crest stage tubes and piezometers using syringes and tubing, pre-rinsed with deionized water. Samples were then placed in rinsed 50 ml screw cap universal tubes for transport. Samples from V-notch weir outflows were collected directly into a 50 ml screw cap universal tube.

Samples were refrigerated overnight, and then tested for pH, conductivity and temperature. The samples were then passed through 0.45 µm Sartorius cellulose nitrate membrane filters before being sent to the University of Leeds for further analysis.

On arrival in Leeds, the water samples were immediately analysed. The absorbance at 665, 470, 465, 436, 400, 360, 265 and 254 nm was measured by UV-Vis spectrophotometry. The DOC concentrations were measured on a sub-set of samples (Analytik Jena Multi NC2100 combustion analyser), and the relationship between absorbance and DOC concentration used to model the DOC concentration of all samples. Any remaining sample is stored at 4 degrees Celsius until all data are checked.

The absorbance and DOC concentrations were used to calculate further metrics: the specific absorbance, and E4:E6 ratio. The absorbance and DOC measurements were used to calculate SUVA254 (absorbance at 265nm divided by DOC concentration) and the E4:E6 ratio (absorbance at 465 nm divided by 665 nm). SUVA254 is considered a proxy for the aromatic carbon content of the water, and the E4:E6 indicates the fulvic to humic ratio of the DOC.

5.5. Particulate organic matter

The production and transport of particulate organic matter (POM) was monitored at the two sites with significant sources of surface erosion (the bare peat and *Calluna*-dominated sites) using 'TIMS' units (Time-Integrated Mass Flux Sampler). A set of 10 TIMS units was installed at each mini-catchment within these sites in the autumn of 2020.

5.6. Peat depth

Changes in the height of the peat surface above the underlying mineral substrate were monitored at the bare peat sites using peat anchors. This enabled quantification of rates of erosion/accumulation of the peat surface, as well as the 'bog breathing' effect of the peat mass swelling/shrinking in wetter/drier conditions.

5.7. Other weather variables

At the species dominated sites, ground and air temperature were monitored continuously. Barometric pressure was also recorded continuously in order to compensate automated water table measurement.

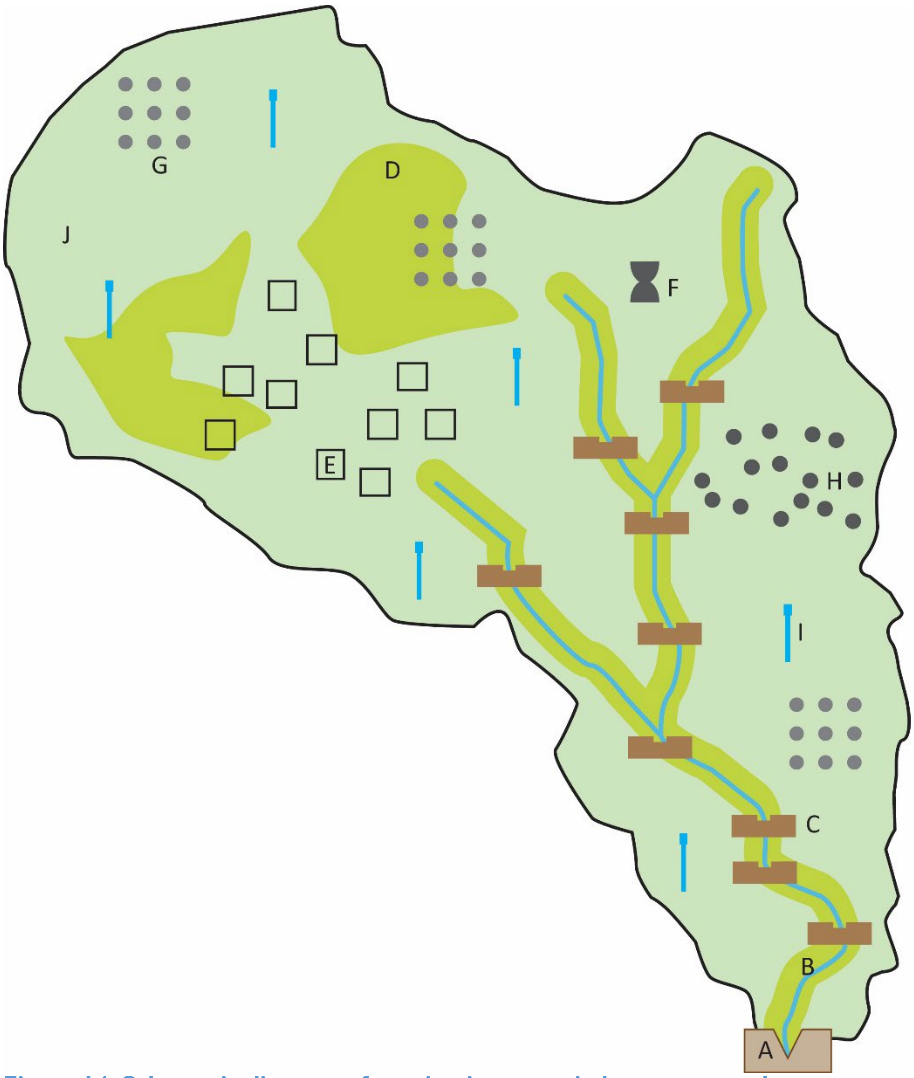

Figure 14: Schematic diagram of monitoring setup in bare peat catchments.

A: V-notch weir with Skye (replaced by Hobo in 2020–21) pressure sensors and Trutrak Omni capacitance sensor measuring catchment discharge

B: Flow pathways with *Sphagnum* planting at density of ~34 plugs m^{-2}

C: Gully blocks – a combination of stone and timber dams; in general the stone dams were installed towards the bottom of the catchment and the timber dams towards the top of the catchment

D: *Sphagnum* patches planted ~5 plugs m^{-2}

E: Ten 2m x 2m vegetation quadrats distributed randomly within catchment

F: Rain gauge

G: Crest stage tubes – installed as a three by three grid of nine tubes, at a spacing of 30cm between each tube

H: Dipwell cluster – 15 dipwells randomly located within a 30m x 30m square

I: Peat anchor – 10mm cross-section threaded bar pushed down through the peat and anchored into the mineral substrate

J: Restored vegetation within catchment

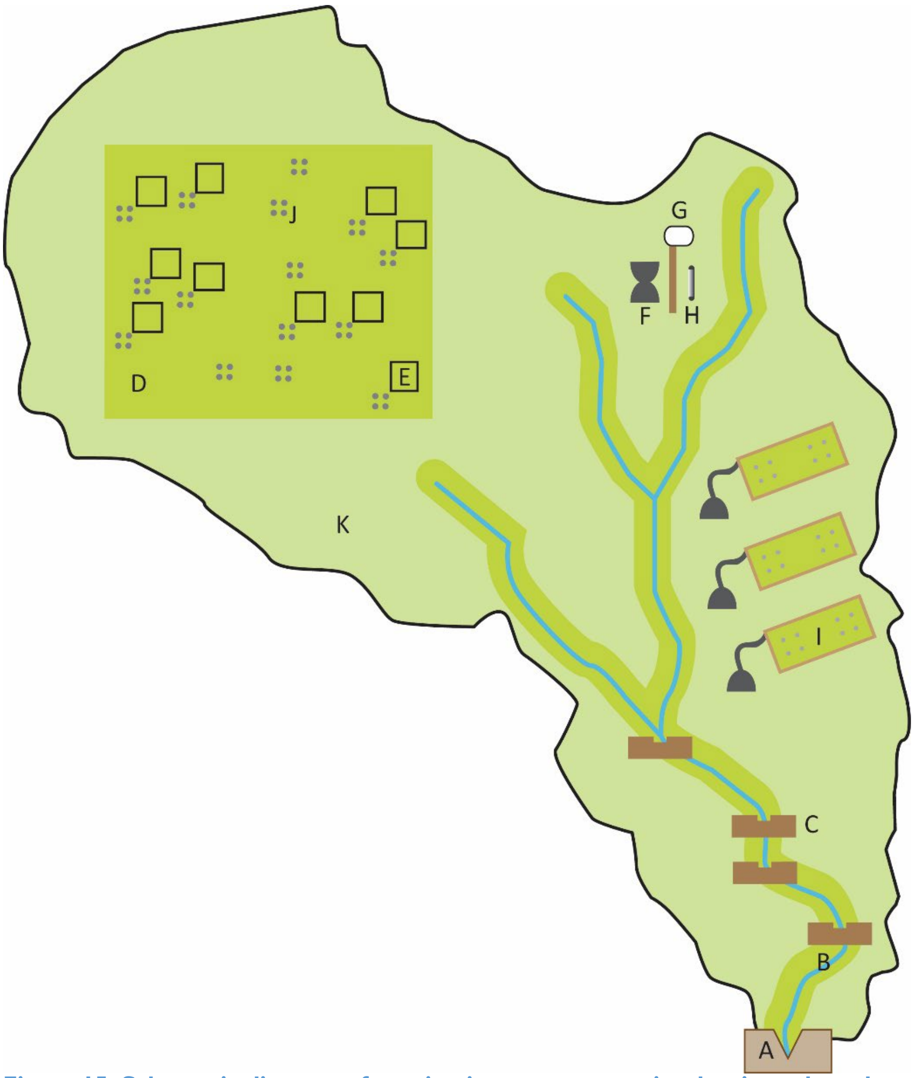

Figure 15: Schematic diagram of monitoring setup at species dominated catchments.

A: V-notch weir with Trafag pressure sensor measuring catchment discharge

B: Flow pathways with *Sphagnum* planting at density of 4 plugs m^{-2}

C: Gully block (Cal.SphaGB catchment only)

D: 30m x 30 m area of *Sphagnum* planted at 4 plugs m^{-2}

E: Ten 2m x 2m vegetation quadrats distributed randomly within area D

F, G, H: Atmospheric station including rain gauge, atmospheric/soil temperature sensors, and barometric pressure sensor – one station per site

I: Three 1 m x 3 m intensive *Sphagnum* plots, planted at density of 100 plugs m^{-2}. Each plot contains two dipwells, two 5 cm piezometers, two 10 cm piezometers, two crest stage tubes, one Solinst auto logger recording continuous water table data in one intensive plot, and a tipping bucket mechanism logging run-off from the plot using a Tinytag count logger.

J: Dipwell cluster with 15 locations each with one dipwell, one 5 cm piezometer, one 10 cm piezometer and one crest stage tube.

K: Catchment *Sphagnum* planting at density of 1 plug m^{-2}

Table 11. Monitoring programme across all sites in the ML2020 D2 project

Monitored variables	Bare peat	*Calluna*	*Eriophorum*	*Molinia*
Rainfall (rain gauge)	01/2016–2021	07/2017–2021	07/2017–2021	09/2017–2021
Catchment stream discharge (v-notch weir)	01/2016–2021	08/2017–2021	08/2017–2021	09/2017–2021
Streamflow water chemistry (samples from v-notch weir)	01/2016–2021	11/2018–2021	11/2018–2021	11/2018–2021
Surface water chemistry (samples from crest stage tubes)	–	11/2018–2021	11/2018–2021	11/2018–2021
Sub-surface water chemistry (samples from piezometers)	–	11/2018–2021	11/2018–2021	11/2018–2021
Water table (manual surveys)	2016–2021 (autumn campaigns)	09/2017–2021	09/2017–2021	12/2017–2021
Water table (continuous data)	2016/01–2021	07/2017–2021	11/2017–2021	09/2017–2021
Overland flow generation (manual surveys)	2018–2020 (autumn campaigns)	09/2017–2021	09/2017–2021	12/2017–2021
Overland flow generation (continuous)	–	07/2017–2021	07/2017–2021	09/2017–11/2019. Control only continued to 2021.
Soil moisture (continuous)	2021	–	–	–
Sub-surface flow (manual surveys)	–	10/2018–2021	11/2018–2021	08/2018–2021
Particulate organic matter erosion/transport (TIMS units in streams)	10/2020	10/2020	–	–
Peat depth (peat anchors)	2019–2021	–	–	–
Vegetation cover (2 x 2 m quadrats, all species; all *Sphagnum* combined)	2016–2021	2018–2021	2018–2021	2018–2021
Sphagnum surveys (1 x 1 m quadrats, individual *Sphagnum* species surveyed)	2018, 2020	-	-	-
Sphagnum plug development (fixed point photography)	2018–2020	04/2019–2021	04/2019–2021	04/2019–2021
Barometric pressure	–	07/2017–2021	07/2017–2021	09/2017–2021
Air and ground temperature	–	08/2017–2021	08/2017–2021	11/2017–2021

6. Climate

Climatic variability is the most important natural force behind changing hydrology regimes at peatland sites, influencing stream discharge, overland flow, water tables and even DOC production and release in headwater peatlands. It is therefore important to contextualise hydrological analyses and water quality results with an understanding of changes in climatological variables during the periods of monitoring.

To provide context to the results from the bare peat and species dominated sites, summaries of the climate during the monitoring periods are presented below.

6.1. Climate at bare peat sites

Rainfall was monitored at a 10-minute time interval from 2010 to 2021. Aside from some gaps in the dataset due to technical issues, this monitoring therefore produced a high-resolution and long-term record, providing context for results presented in other chapters of this report. Summarised results are presented in Figure 16 as totals per day, month, quarter and autumn (September – December, to coincide with the annual water table monitoring campaigns) for the duration of the monitoring period.

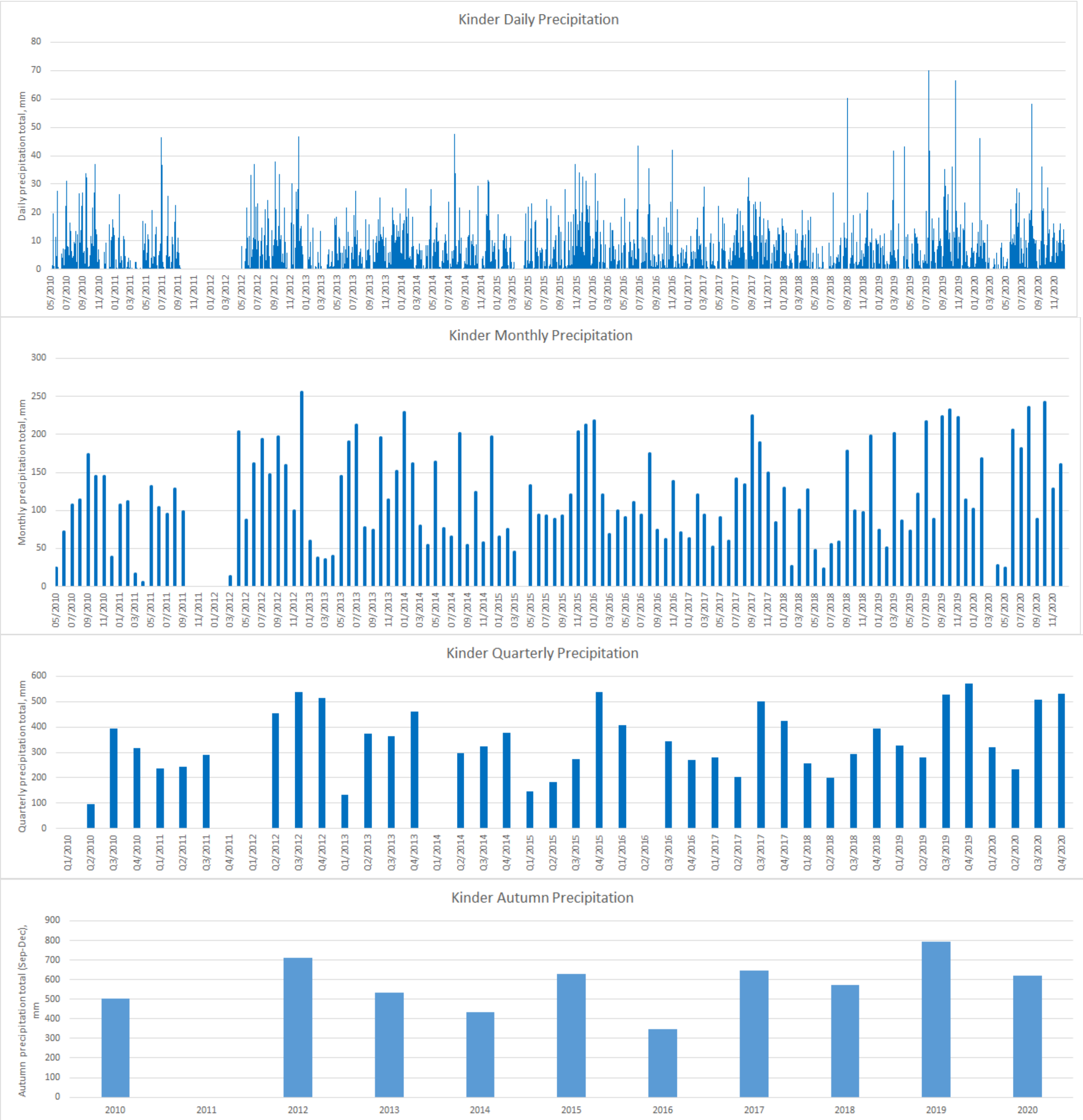

Figure 16: Rainfall totals on Kinder Scout per day (top), month, quarter and autumn (September – December to coincide with annual water table monitoring campaigns) (bottom)

6.2. Climate at species dominated sites

The monitoring at species-dominated sites is examined in this report from 2018-04-01 to 2021-04-01 (three years, one pre and two post treatment) for mini catchments and from 2018-09-01 to 2020-09-01 for intensive *Sphagnum* planted plots.

The climate (rainfall and air temperature) spanning these periods is displayed in Figure 17, Figure 18, Figure 19 and Figure 20 below in increasing levels of temporal resolution. The periods of experiments at catchment level (a) and intensive plot level (b) are different as stated above and therefore project years for each are different.

The ‘project year’ annual rainfall totals and temperatures (min, max and mean) are stated in Table 12. Mean daily temperatures here are maximum of day + minimum of day / 2, so a mean annual temperature is the mean of all the daily means. Mean annual minimum daily temperature is the mean of the minimum temperature observed each day throughout the year and similarly for maximum.

Project year 0 or pre-treatment for both cluster mini catchment and intense plots at all species dominated locations exhibit lower precipitation than the post period years/year as parts of 2018 were particularly dry especially the late spring and summer and to a lesser extent autumn. Temperatures – mean, max or min – are all generally higher in project year 0 and hence this was comparatively a relatively warm and dry year compared to subsequent project years.

Clearly more detail can be gained when seasonal and monthly fluctuations are examined and here these are displayed as calendar seasons and months not within project years. These figures and tables are here to be referred to through the rest of the report to help relate changes reported to possible parallel changes in climate.

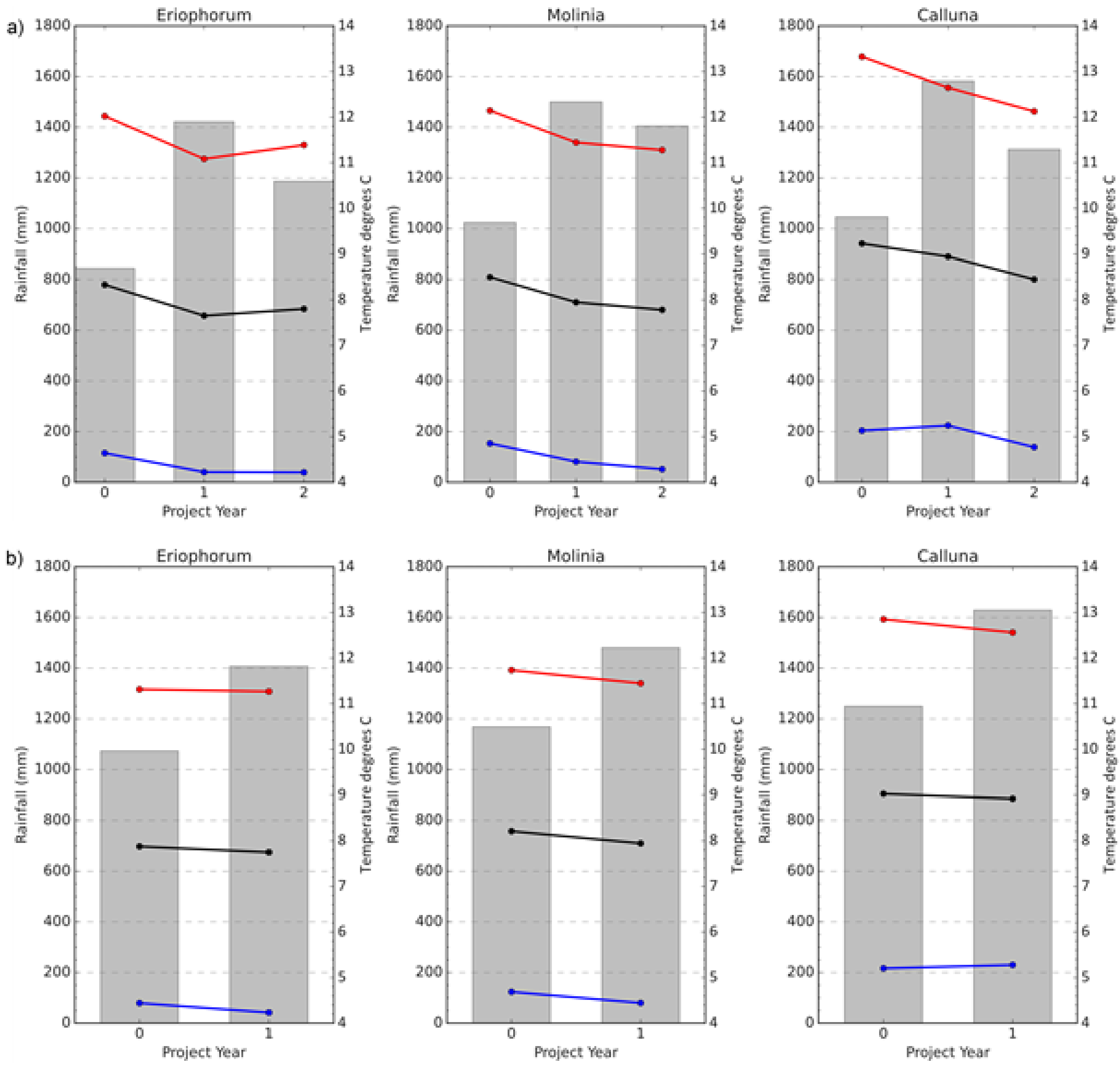

Figure 17. Project year rainfall sum and mean temperature data for min, mean, and max daily temperatures.
a) mini catchment cluster analyses and b) intensive plot analyses. Years of the project for cluster are 2018-04-01 to 2019-04-01, 2019-04-01 to 2020-04-01 and 2020-04-01 to 2021-04-01 and for the intensive plots 2018-09-01 to 2019-09-01 and 2019-09-01 to 2020-09-01.

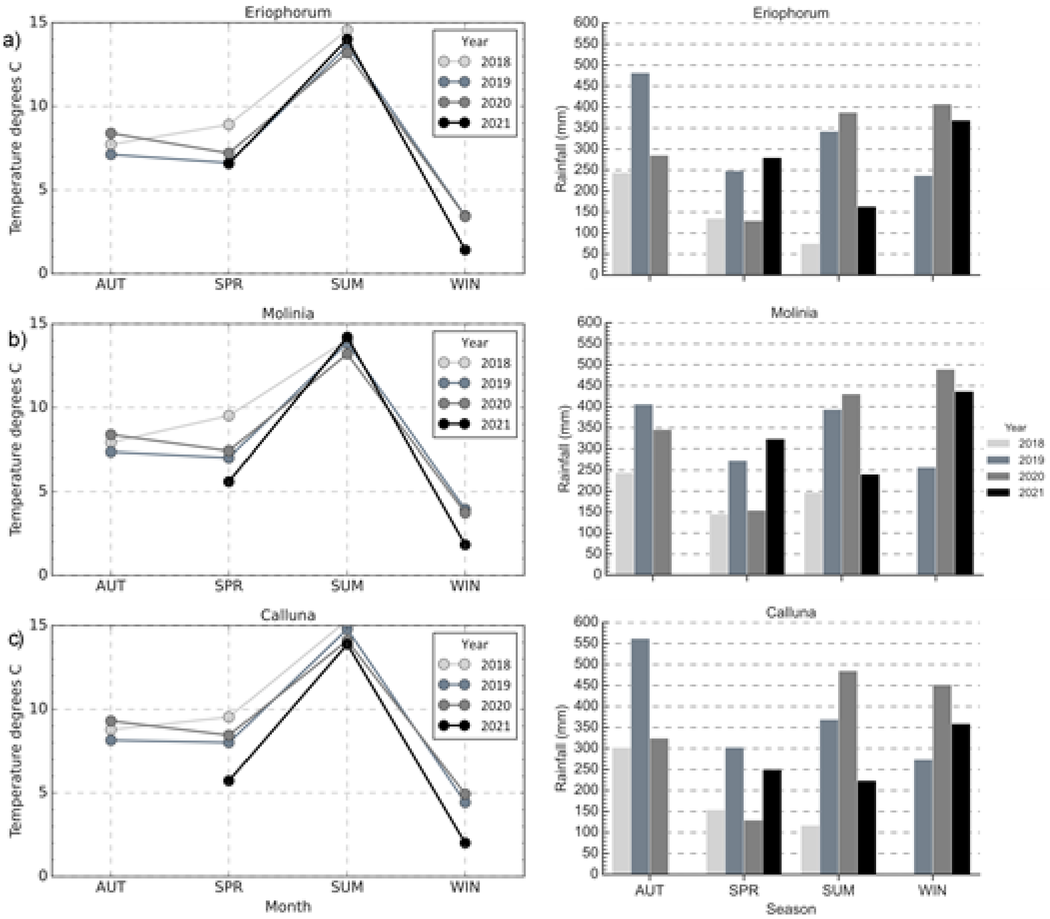

Figure 18. Overlaid (by year) seasonal temperature (mean of mean daily temperature) records together with comparison of rainfall totals each season in successive years at each species dominated site (a–c).

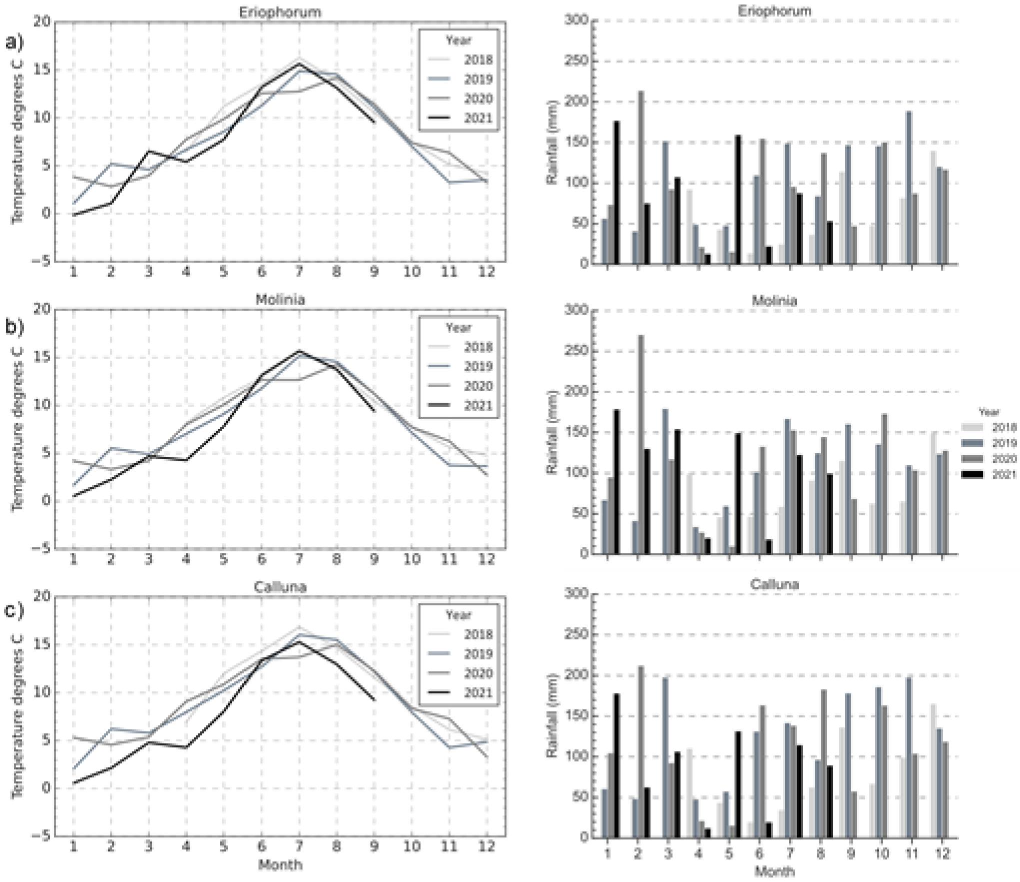

Figure 19. Overlaid (by year) monthly temperature (mean of mean daily temperature) records together with comparison of rainfall totals each month in successive years at each species dominated site (a–c).

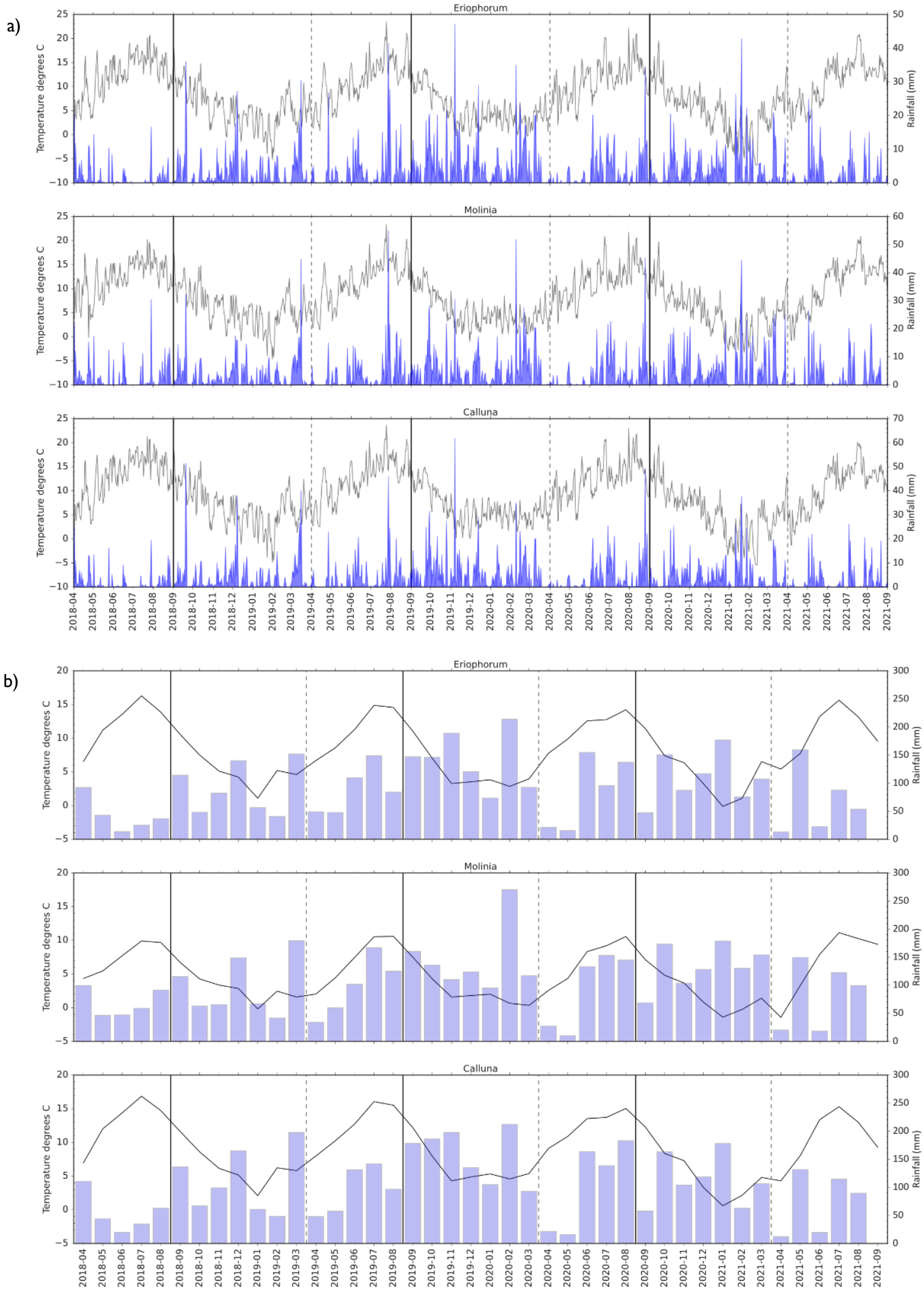

Figure 20: Time series rainfall and temperature at Species Dominated sites.
a) mean daily temperature and daily rainfall sum and b) the mean of mean daily temperature and total rainfall for each month for each species dominated location. Solid black and dashed grey vertical lines delimit the starting points of years of the project for intensive (2018-09-01, 2019-09-01) and cluster (2018-04-01, 2019-04-01, 2020-04-01) sites respectively.

Table 12. Temperature and rainfall data for species dominated sites.
a) 'project' years of the intensive or cluster studies (based on years pre and after treatment occurring) and for b) calendar seasons and c) months for each species dominated location. Rainfalls are totals and temperatures are derived from mean daily temperature.

a)

		Eriophorum				Molinia				Calluna			
	Year of project	Mean Daily Min	Mean Daily Max	Mean Daily Mean	Rain sum	Mean Daily Min	Mean Daily Max	Mean Daily Mean	Rain sum	Mean Daily Min	Mean Daily Max	Mean Daily Mean	Rain sum
Cluster	0	4.6	12.0	8.3	843.6	4.9	12.1	8.5	1023.4	5.1	13.3	9.2	1045.4
	1	4.2	11.1	7.7	1421.2	4.5	11.4	7.9	1499.6	5.2	12.6	8.9	1581.6
	2	4.2	11.4	7.8	1186.2	4.3	11.3	7.8	1404.4	4.8	12.1	8.4	1312.4
Intensive	0	4.4	11.3	7.9	1072.6	4.7	11.7	8.2	1167.8	5.2	12.8	9.0	1249.0
	1	4.2	11.3	7.7	1406.4	4.4	11.4	7.9	1480.4	5.3	12.6	8.9	1628.8

b)

	Eriophorum				Molinia				Calluna			
Season year	Mean Daily Min	Mean Daily Max	Mean Daily Mean	Rain sum	Mean Daily Min	Mean Daily Max	Mean Daily Mean	Rain sum	Mean Daily Min	Mean Daily Max	Mean Daily Mean	Rain sum
SPR 2018	4.4	13.4	8.9	136.2	4.9	14.1	9.5	145.6	4.5	14.6	9.5	154.2
SUM 2018	9.2	19.9	14.6	75.2	9.1	19.0	14.1	197.2	9.5	21.1	15.3	117.0
AUT 2018	4.6	10.8	7.7	244.2	4.8	11.1	7.9	244.0	5.4	12.2	8.8	302.4
WIN 2019	1.2	5.7	3.5	237.2	1.7	6.2	4.0	257.2	1.9	7.0	4.4	274.2
SPR 2019	2.4	10.8	6.6	248.6	2.7	11.3	7.0	273.0	3.3	12.8	8.0	308.0
SUM 2019	9.4	17.8	13.6	342.6	9.5	18.2	13.9	393.6	10.2	19.4	14.8	369.4
AUT 2019	4.4	9.9	7.1	481.8	4.5	10.3	7.4	406.2	5.3	11.0	8.1	562.2
WIN 2020	1.1	5.7	3.4	407.4	1.5	6.0	3.7	489.2	2.5	7.3	4.9	452.0
SPR 2020	2.1	12.3	7.2	129.6	2.4	12.4	7.4	154.4	3.2	13.7	8.4	129.6
SUM 2020	9.3	17.1	13.2	387.6	9.4	17.0	13.2	430.6	10.1	18.1	14.1	485.0
AUT 2020	5.3	11.5	8.4	285.4	5.2	11.6	8.4	345.6	6.0	12.6	9.3	324.8
WIN 2021	-0.9	3.7	1.4	368.8	-0.3	3.9	1.8	436.8	-0.2	4.3	2.0	359.2
SPR 2021	2.1	11.1	6.6	279.8	1.1	10.1	5.6	323.4	0.9	10.6	5.7	250.2
SUM 2021	9.7	18.4	14.0	163.4	9.8	18.6	14.2	240.4	9.2	18.5	13.9	223.6

c)

	Eriophorum				Molinia				Calluna			
Month Year	Mean Daily Min	Mean Daily Max	Mean Daily Mean	Rain sum	Mean Daily Min	Mean Daily Max	Mean Daily Mean	Rain sum	Mean Daily Min	Mean Daily Max	Mean Daily Mean	Rain sum
Apr-18	3.1	10.0	6.5	92.4	4.3	12.0	8.2	99.4	3.1	10.9	7.0	110.4
May-18	5.6	16.8	11.2	42.8	5.5	16.2	10.8	46.2	5.8	18.2	12.0	43.8
Jun-18	7.9	19.1	13.5	13.6	7.7	18.1	12.9	47.0	8.3	20.4	14.4	19.8
Jul-18	10.0	22.6	16.3	25.0	9.9	21.6	15.7	59.0	10.0	23.7	16.9	34.6
Aug-18	9.7	18.0	13.9	36.6	9.7	17.3	13.5	91.2	10.1	19.3	14.7	62.6
Sep-18	6.7	14.4	10.6	114.2	6.7	14.2	10.4	115.6	7.2	16.0	11.6	136.4
Oct-18	4.0	11.0	7.5	48.0	4.3	11.1	7.7	62.8	4.8	12.4	8.6	67.0
Nov-18	3.1	7.1	5.1	82.0	3.4	7.9	5.6	65.6	4.1	8.2	6.1	99.0
Dec-18	2.3	6.1	4.2	140.0	2.8	6.7	4.8	148.8	3.1	7.2	5.2	165.2
Jan-19	-0.7	2.9	1.1	56.4	-0.2	3.6	1.7	67.0	0.1	4.1	2.1	60.6
Feb-19	2.1	8.3	5.2	40.8	2.5	8.6	5.5	41.4	2.7	9.8	6.2	48.4
Mar-19	1.5	7.7	4.6	151.8	1.6	8.2	4.9	179.4	2.2	9.4	5.8	197.6
Apr-19	1.8	11.6	6.7	49.0	2.0	12.1	7.0	34.0	2.4	13.5	8.0	48.0
May-19	4.0	13.2	8.6	47.8	4.4	13.8	9.1	59.6	5.2	15.3	10.2	57.4
Jun-19	7.2	15.4	11.3	109.6	7.5	16.1	11.8	101.6	8.1	17.3	12.7	131.2
Jul-19	10.5	19.3	14.9	148.8	10.5	19.8	15.2	167.0	11.2	20.9	16.1	141.8
Aug-19	10.6	18.5	14.6	84.2	10.6	18.5	14.6	125.0	11.2	19.8	15.5	96.4
Sep-19	7.6	14.5	11.1	147.0	7.5	14.9	11.2	160.4	8.5	15.9	12.2	178.4
Oct-19	4.3	9.8	7.0	146.0	4.3	10.0	7.2	135.8	5.2	10.8	8.0	186.0
Nov-19	1.3	5.3	3.3	188.8	1.6	5.9	3.7	110.0	2.2	6.4	4.3	197.8
Dec-19	1.6	5.5	3.5	120.2	1.8	5.5	3.7	123.8	2.8	6.9	4.9	135.2
Jan-20	1.5	6.2	3.8	73.4	2.0	6.4	4.2	95.0	3.1	7.6	5.3	104.8
Feb-20	0.2	5.5	2.8	213.8	0.6	6.0	3.3	270.4	1.7	7.4	4.6	212.0
Mar-20	0.1	7.9	4.0	92.6	0.4	8.1	4.2	117.0	1.2	9.6	5.4	92.6
Apr-20	2.2	13.3	7.8	21.4	2.6	13.5	8.0	27.2	3.3	14.9	9.1	21.4
May-20	4.1	15.7	9.9	15.6	4.3	15.8	10.1	10.2	5.0	16.8	10.9	15.6
Jun-20	8.2	16.9	12.6	154.8	8.3	17.0	12.7	132.8	9.1	18.0	13.5	163.6
Jul-20	9.4	16.2	12.8	95.6	9.2	16.1	12.7	153.0	10.0	17.4	13.7	138.4
Aug-20	10.2	18.2	14.2	137.2	10.6	18.0	14.3	144.8	11.2	18.9	15.0	183.0
Sep-20	7.3	15.6	11.5	47.4	7.1	15.3	11.2	68.6	7.9	16.7	12.3	57.6
Oct-20	4.7	10.1	7.4	150.6	4.8	10.6	7.7	173.2	5.6	11.1	8.4	163.2
Nov-20	3.8	9.0	6.4	87.4	3.7	8.9	6.3	103.8	4.4	10.1	7.3	104.0
Dec-20	1.2	5.3	3.3	116.8	0.8	4.7	2.7	128.0	1.4	5.3	3.3	118.6
Jan-21	-2.3	2.1	-0.1	176.8	-1.4	2.5	0.5	178.6	-1.5	2.6	0.6	178.0
Feb-21	-1.7	3.8	1.1	75.2	-0.3	4.8	2.3	130.2	-0.7	5.0	2.2	62.6
Mar-21	3.0	10.1	6.5	107.4	1.4	8.0	4.7	154.0	1.1	8.5	4.8	106.4
Apr-21	0.0	10.9	5.4	13.0	-1.4	10.0	4.3	20.2	-1.9	10.5	4.3	12.2
May-21	3.3	12.2	7.7	159.4	3.3	12.3	7.8	149.2	3.3	12.8	8.0	131.6
Jun-21	8.0	18.5	13.2	22.4	7.9	18.4	13.2	18.4	7.7	19.1	13.4	19.6
Jul-21	11.1	20.2	15.7	87.6	11.1	20.2	15.7	122.6	10.6	20.0	15.3	114.6
Aug-21	9.9	16.4	13.1	53.4	10.3	17.3	13.8	99.4	9.4	16.5	13.0	80.4

7. Limitations

On 11/08/2020 portions of the *Calluna* site including both control and treatment catchments were subjected to a light aerial application of lime pellets unintentionally distributed by a helicopter applying the pellets to an adjacent site. This overspill was identified on the day of occurrence, and with no rain occurring overnight, steps were taken to mitigate the issue during the following day. A team manually removed the pellets from within all vegetation quadrats affected, including the intensive plots. It is thought that a high proportion of the lime was removed from these areas and what remained was so minimal as to be unlikely to contribute to any significant changes in vegetation or water chemistry within these areas. However, it was not possible to remove all pellets from whole catchments. The even distribution and light covering across both control and treatment catchments mean that the effects of this incident are likely to be minimal, and indeed the incident could not be detected in the water samples gathered immediately after the incident, or any samples gathered subsequently.

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MoorLIFE 2020

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