MOORS
FOR THE FUTURE
PARTNERSHIP

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

CHAPTER 1: SUMMARY

MoorLIFE 2020

MoorLIFE 2020 Final Report:
Action D2

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

Chapter 1: Summary

2022

Funded by:

Life

NATURA 2000

Prepared by:

MOORS FOR THE FUTURE PARTNERSHIP

UNIVERSITY OF LEEDS

MANCHESTER 1824
The University of Manchester

Prepared by

Moors for the Future Partnership
The Moorland Centre, Edale, Hope Valley, Derbyshire, S33 7ZA, UK
www.moorsforthefuture.org.uk

Contact: moors@peakdistrict.gov.uk

Suggested citation:

Allott, T.E.H., Blundell, A., Chandler, D., Evans, M.G, Margetts, J.J., Moody, C.S., Pilkington, M.G., Rees, J., Ritson, J.P, Shuttleworth, E.L, Spencer T. (2022). *Chapter 1: Summary* in Moors for the Future Partnership (2022) *Monitoring the biodiversity and ecosystem service impacts of restoration of degraded blanket bog sites.* Final report of the MoorLIFE 2020 project Action D2: Moors for the Future Partnership, Edale.

Acknowledgements:

Thanks go to the many staff members who made this project possible, including Tom Aspinall, David Botcherby, Denzil Broadhurst, Andy Farmer, Sam Heap, Patricia Justin, Luke Nelson, Jane Price, Tony Rogers, Barry Soames, Geoff Sweeney, Elizabeth Townsend, Adrian West-Samuel and Natasha Yamamoto. Additional thanks go to the many individuals who volunteered their time, who are too numerous to list here.

Contents

List of Figures

List of Tables

1. Executive summary

This study assessed the impacts on ecosystem services of a range of blanket bog restoration techniques. Heavily degraded sites dominated by bare peat were revegetated, gullies were blocked and *Sphagnum* mosses were reintroduced. Sites dominated by single species – hare's tail cotton-grass (*Eriophorum vaginatum*), common heather (*Calluna vulgaris*) and purple moor-grass (*Molinia caerulea*) – were diversified by reintroducing *Sphagnum* mosses.

1.1. Bare peat sites

Results showed important changes to ecosystem services at the bare peat sites including:

Vegetation diversity

- Almost 100% vegetation cover within 5–7 years of initial treatment (starting state 0% vegetation; 100% bare peat)
- Approximately 100% cover of blanket bog indicator species within 10 years of initial treatment
- Almost no 'natural' re-establishment of *Sphagnum* mosses where they weren't actively re-introduced
- Approximately 25% cover of *Sphagnum* mosses in areas where they were planted on undulating ground (~5 plugs m^{2-1}), 6 years after planting
- Approximately 85% cover of *Sphagnum* mosses in flow pathways in the catchment where they were planted, 6 years after planting

Water table and soil moisture

- Water tables rose slowly but steadily (~7mm yr^{-1}) for up to 17 years following restoration (this is an average figure from a large number of bare peat sites with diverse topographies receiving a range of restoration techniques including revegetation and a range of gully blocking methods)
- Initial results using new soil moisture monitoring technology indicated that near-surface soil moisture was significantly higher at revegetated sites than bare peat sites, with a possible additional increase in near-surface soil moisture associated with dense *Sphagnum* cover
- Near-surface soil moisture appeared to remain higher for significantly longer at revegetated sites than at bare peat sites during prolonged periods without rainfall, with important implications for drought resilience

Stream discharge

- Revegetation of bare peat led to a step change in stream flow attenuation in storm events, with peak discharge reduced (by 45 percentage points) and delayed (by 183 percentage points)
- Gully blocking enhanced these benefits, with peak discharge further reduced (by an additional 5 percentage points) and delayed (by an additional 217 percentage points)
- No further changes were observed as these initial interventions matured
- The addition of *Sphagnum* plug plants, four years after initial revegetation and gully blocking, initiated new trajectories of change to peak discharge and lag times
- Six years after *Sphagnum* planting, peak discharge was reduced by 65 percentage points (relative to untreated control); lag time was increased by 680 percentage points
- This has important implications for Natural Flood Management at the catchment scale, as modelling has suggested that if this treatment were applied across large areas, these changes to

storm flow characteristics may result in significant reduction in peak flows at the wider catchment scale
- The *Sphagnum* is still spreading (laterally and vertically) so further benefits to NFM are anticipated

Sediment generation and transport

- Revegetation of bare peat led to a ~99% reduction of sediment erosion and transport. This represents an effective halt of carbon losses from erosion and sediment load being transported to the river network

Water chemistry

- Applications of lime and fertiliser had short-term effects on water chemistry (raised calcium concentration, raised pH, depressed dissolved organic carbon (DOC) concentration) but no effects were observable beyond four years after initial treatment
- Restoration of heavily degraded bare peat has no observable effect on DOC concentration or flux

1.2. Sites dominated by single species

Results at sites dominated by single species are summarised below:

1.2.1. Calluna site

Vegetation diversity

- *Sphagnum* was successfully introduced into dense heather cover. After two years, cover had increased by 5 percentage points (*pp*) relative to control where planted at 4 plugs m^{-2}, and by between 22–48 pp where planted at 100 plugs m^{-2}.
- Little change was observed in the dominance of *Calluna* during this time.
- *Sphagnum* cover increased the number of indicator species present. Where planted at high density into an area of 50% *Calluna* cover, all Common Standards Monitoring (CSM) criteria for achieving favourable condition were met.

Water table

- Manual water table measurements have not yet shown any statistically significant changes on this site.
- Continuous water table measurements presented as mixed picture with both rises and falls in different catchments. However although statistically significant, all changes seen were slight and further monitoring is required.

Stream discharge

- There was not yet any statistically significant change found in relative peak discharge in either catchment after treatment

- The relative peak lag time became significantly longer in the post-treatment period. Gully blocking had more effect on peak lag than *Sphagnum* planting alone during these early post-treatment years.
- A significant decrease in relative run-off co-efficient was found after treatment, suggestive of *Sphagnum* increasing the holding capacity of the catchment.
- No difference was found in the Hydrograph Storm Index.

Overland flow generation and surface run-off

- The treated catchments showed an increase in overland flow generation from the before to the after periods, compared to control.
- In the *Sphagnum* treated run-off plots with the highest *Sphagnum* cover (48% in 2021) a substantial and significant increase in start lag time relative to control was found.

Water quality

- Baseline sediment transport figures were established during this monitoring period. This element of the monitoring should be repeated in future once *Sphagnum* coverage has increased to look for change.
- No change in pH was found.
- DOC flux appeared to decrease in the *Sphagnum* catchment in the first years after treatment. This result was statistically significant, but continued monitoring is required to verify this finding.
- Gully blocking appeared to increase the DOC concentration in the first years after installation, due to disturbance, but this change was small and not statistically significant.

1.2.2. Eriophorum site

Vegetation diversity

- *Sphagnum* was successfully introduced into dense cotton-grass cover. After two years, cover had increased by 10 *pp* relative to control where planted at 4 plugs m^{-2}, and by 53 *pp* where planted at 100 plugs m^{-2}.
- Little change was observed in the dominance of *Eriophorum* during this time.

Water table

- Manual water table measurements have not yet shown any change in the wider catchment, but showed a small but significant rise of 18 mm where *Sphagnum* was planted at 100 plugs m^{-2}.
- Continuous water table measurements provided further evidence of this change, showing water table had risen by 13.8 mm. The water table also appeared to spend a higher proportion of time nearer the surface after planting, compared to control.

Stream discharge

- Relative peak discharge decreased at the treatment plot. The change was statistically significant.
- No statistically significant difference was found in the relative peak lag time in the first years after treatment.

- There was no statistically significant reduction in relative run-off co-efficient found after treatment, and results were unclear due to confounding factors.
- The Hydrograph Storm Index was not significantly different after treatment.

Overland flow generation and surface run-off

- The treated catchments showed little change in overland flow generation from the before to the after periods, compared to control.
- In the *Sphagnum* treated catchment, little change in start lag time or peak lag time relative to control was found.

Water quality

- No change in pH was found.
- DOC flux appeared to decrease, but not significantly, in the first years after treatment. Continued monitoring is required to verify whether this finding is due to the treatment.
- DOC in overland flow water at surface, 5cm and 10cm depths was significantly lower in the *Sphagnum* treated catchment after treatment. However, this finding was not replicated in the intensively planted plots, so further monitoring is required.

1.2.3. Molinia site

Vegetation diversity

- *Sphagnum* was successfully introduced into dense purple moor-grass cover. After two years cover had increased by 03 *pp* relative to control where planted at 4 plugs m^{-2}, and by 11 *pp* where planted at 100 plugs m^{-2}.
- Little change was observed in the dominance of *Molinia* during this time.

Water table

- Both small falls and rises in water tables were recorded by manual and continuous measurements, leaving an unclear picture of whether the site has changed during the monitoring period. However, it was found that the control and treatment catchments were hydrologically dissimilar. The treatment catchment water table was closer to surface before and after treatment meaning it has a smaller potential to reduce depth to water table compared to the deeper control.

Stream discharge

- No statistically significant differences in relative peak discharge lag time, run-off co-efficient or HSI were found in the first years after treatment.

Overland flow generation

- A small relative increase in overland flow of 5% was seen in the lower planting density areas, whereas a small relative reduction in overland flow of ~18% was found in the high density planning areas. The effect of *Sphagnum* planting is not yet clear.

Water quality

- No change in pH was found.
- DOC flux appeared to decrease, but not significantly, in the first years after treatment. Continued monitoring is required to verify whether this finding is due to the treatment.
- No changes in electrical conductivity or DOC characteristics were found after treatment.
- Changes in DOC in water at surface, 5cm and 10cm depths were unclear and require further monitoring.

2. Introduction

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 cotton-grass (*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 a similar experimental design, to evidence the impacts of restoration on sites dominated by *Eriophorum*, *Calluna* and *Molinia*.

3. Bare peat sites

Restoration of bare peat sites by revegetation, gully-blocking and *Sphagnum*-planting resulted in multiple benefits to ecosystem services, with subsequent interactions and feedback loops as summarised in Table 1, Figure 1 and Figure 2.

Table 1: Effects of restoration of bare peat on key variables describing blanket bog ecosystem services

Ecosystem Service	**Revegetation**	**Revegetation, gully-blocking, *Sphagnum*-planting**
Biodiversity/habitat	Improved	Additional improvement
Sediment erosion (and associated carbon emissions)	Significant avoided losses	Significant avoided losses
Water table	Gradual rise towards the surface	Gradual rise towards the surface
Soil moisture	Increased	Additional increase
Peak storm streamflow	Decreased	Additional decrease
Storm streamflow lag time	Increased	Additional increase
Dissolved organic carbon in streamflow	Unchanged	Unchanged

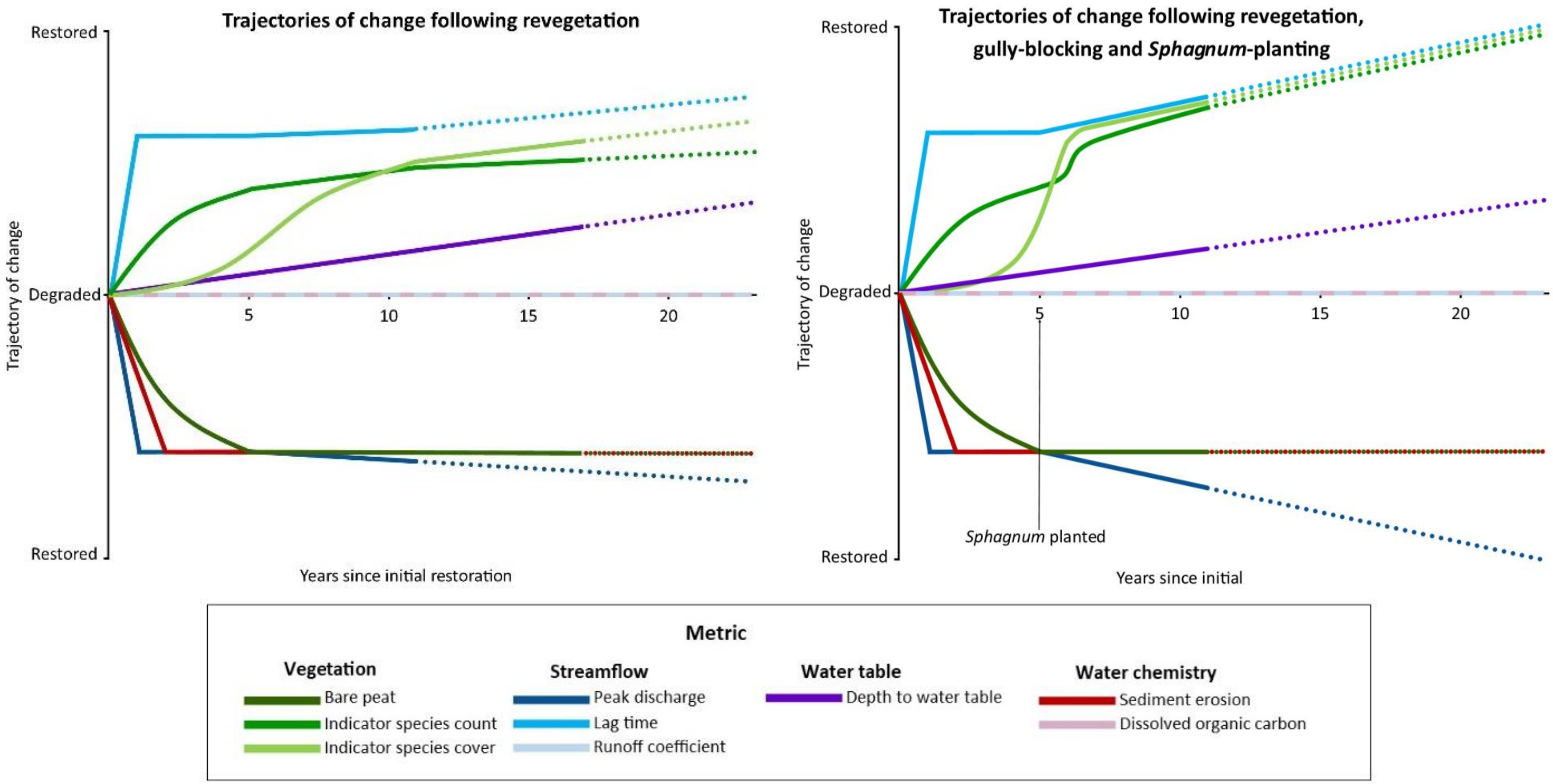

Figure 1: Conceptual graphs showing trajectories of change following restoration of bare peat sites. Adapted from Alderson *et al* (2019). Solid lines indicate observed trends; dotted lines indicate projected trajectories beyond the extent of current monitoring

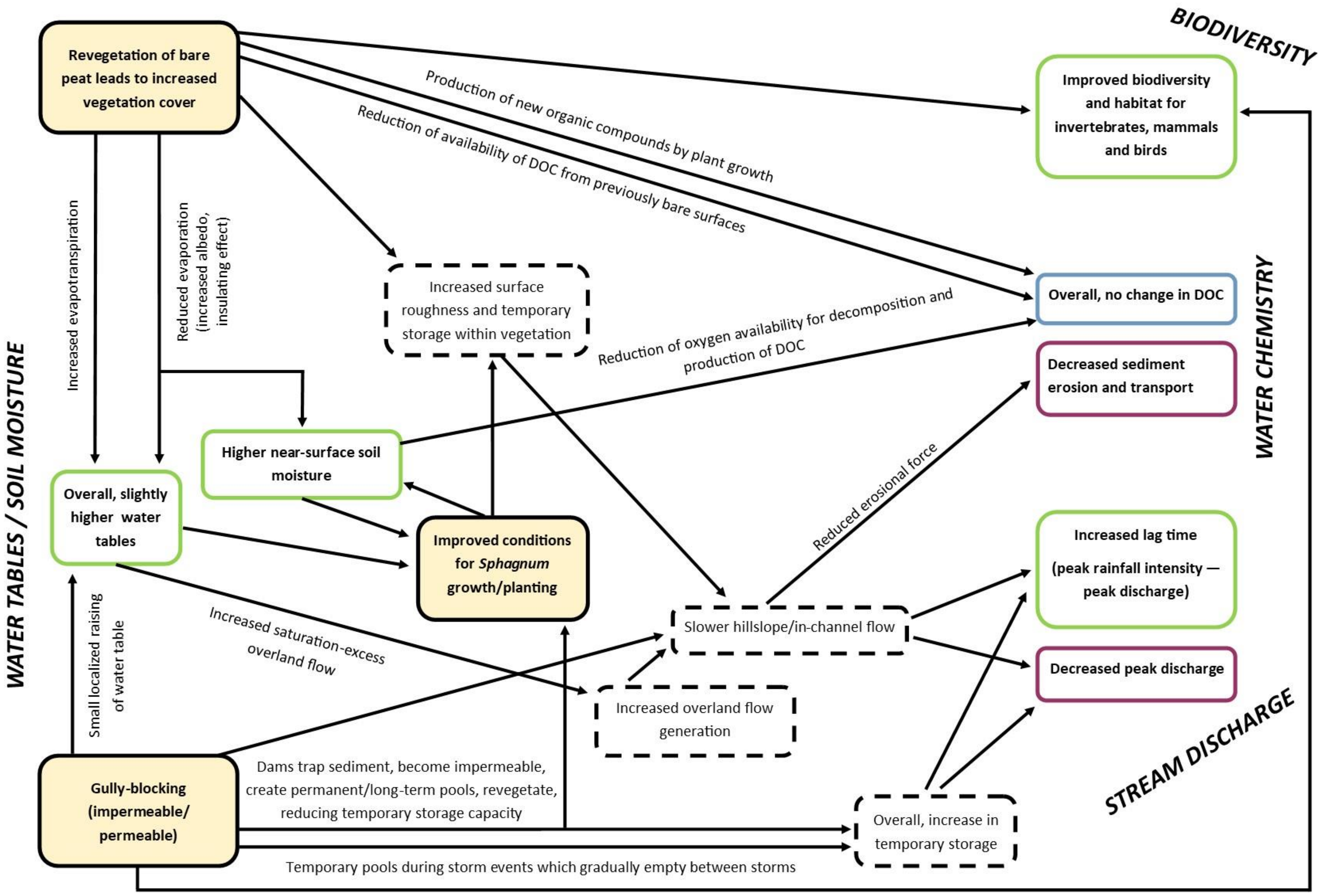

Figure 2: Effects of restoration interventions and their subsequent interactions and outcomes

3.1. Vegetation diversity

Treating areas of bare peat (including large sites dominated by bare peat with minimal extant vegetation) with applications of heather brash, lime, seed, fertiliser and plug plants resulted in comprehensive vegetation cover within five years, dominated by nurse crop grasses included in the seed mix. Over the following years, the vegetation community underwent a succession process through which the nurse crop grasses declined and more natural moorland and blanket bog species increased in percentage cover. While there was variation between sites, the vegetation community tended to comprise ericoids, graminoids and bryophytes in roughly equal proportions, from around seven years after initial treatment (see Figure 3). The development of these multiple canopy layers (ericoids, graminoids and bryophytes) resulted in total vegetation cover exceeding 100% and continuing to increase gradually for at least 17 years after the initial treatment. This maturation of the vegetation community into a complex, dense cover may have important implications for multiple blanket bog functions and processes:

- **Biodiversity:** increased diversity of cover and food for invertebrates, mammals and birds
- **Carbon emissions:** increased protection of the peat surface from wind and rain reduces erosion and production of sediment, avoiding the carbon losses associated with bare peat
- **Carbon sequestration:** accumulation of new plant material may start to form new peat, sequestering carbon from the atmosphere
- **Water tables:** an insulating vegetation layer with higher albedo over previously bare peat reduces warming and drying of the peat, reducing evaporation and maintaining higher water tables. This effect may be limited by increased plant activity increasing evapotranspiration and potentially drawing water tables down
- **Flooding:** increased density and complexity of vegetation cover increases surface roughness, slowing overland flow of water during storm events and reducing flood severity by reducing peak stream discharge and increasing lag time from peak rainfall to peak stream discharge

Within the graminoids, *Deschampsia flexuosa* became the dominant species at several sites; *Eriophorum angustifolium* and *Eriophorum vaginatum* (both indicator graminoid species) were present at almost all sites. There was no evidence of *Molinia caerulea* developing any significant presence as a result of these restoration methods.

Within the ericoids, *Calluna vulgaris*, while establishing at almost all sites, did not come to dominate at the expense of other species.

Within the bryophytes a consistent succession process was observed, with pioneer acrocarpous mosses being replaced by *Polytrichum* spp and/or pleurocarpous mosses once a consolidated vegetation cover had been established. *Sphagnum* mosses did not develop any meaningful presence within the monitored quadrats, even after 17 years following initial treatment, suggesting that they will not recolonize as part of a short-medium term succession process unless they are actively reintroduced. Where they were planted, *Sphagna* achieved ~25% cover on undulating ground, and were approaching 100% cover in some flow pathways, six years after planting. This highlights that *Sphagnum* moss planting can be highly successful on heavily degraded, recently bare peat sites, and is required if *Sphagnum* recolonisation is to be achieved.

On sites where *Sphagnum* mosses were not planted, favourable condition (as per CSM guidelines for blanket bogs) was not achieved, 17 years following initial revegetation – and these sites were not at all close to achieving favourable condition. Where *Sphagna* were planted, favourable condition was nearly (but not quite) achieved. If this were achieved in future years this would likely be the first record of a blanket bog site restored from a bare peat starting state achieving favourable condition under CSM guidelines and would represent a significant milestone in peatland restoration. It should be noted, however, that this site still has an extensive and severe gully network and therefore does not look like an intact blanket bog.

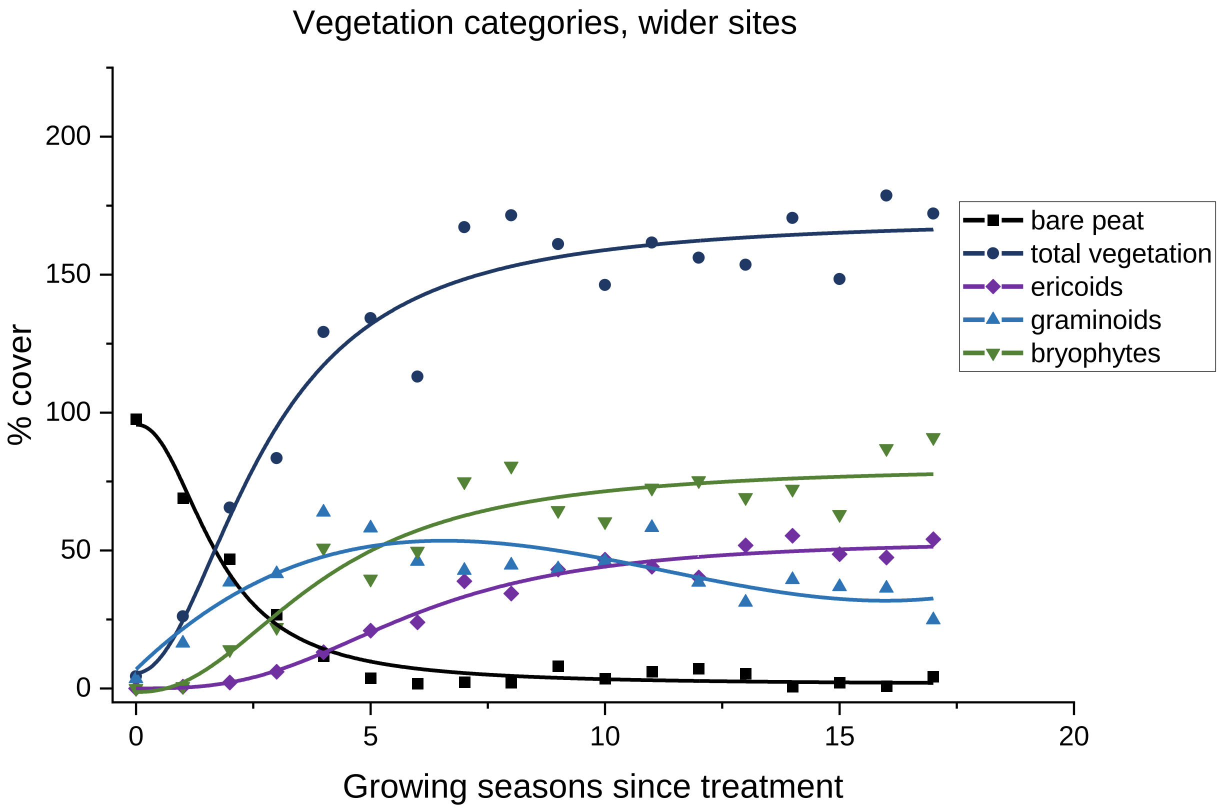

Figure 3: Vegetation community composition following revegetation at a range of bare peat sites across the South Pennines. Total vegetation cover may >100% due to layering of different categories' canopies. Datapoints represent median value of data from all sites (n varied from 3 to 11 between years)

3.2. Water table

Monitoring of water tables at revegetated, previously severely degraded bare peat sites across the South Pennines showed that water tables rose steadily but slowly by 6–8 mm yr^{-1} for up to 17 years following treatment, although there was strong variability between sites, likely associated with severity of historic erosion (see Figure 4). Results from annual campaigns of weekly measurements in manual dipwells were consistent with those from continuous data from dipwells with water level loggers. No significant changes to water table recession rates following rainfall were observed following treatment, although peak water table depth (the closest-to-surface water table depth recorded following a rainfall event) rose by ~10 mm yr^{-1} following treatment; this rise was consistent with the rate of mean water table rise. The rate of water table recovery appeared to be limited by severity of historic gully erosion.

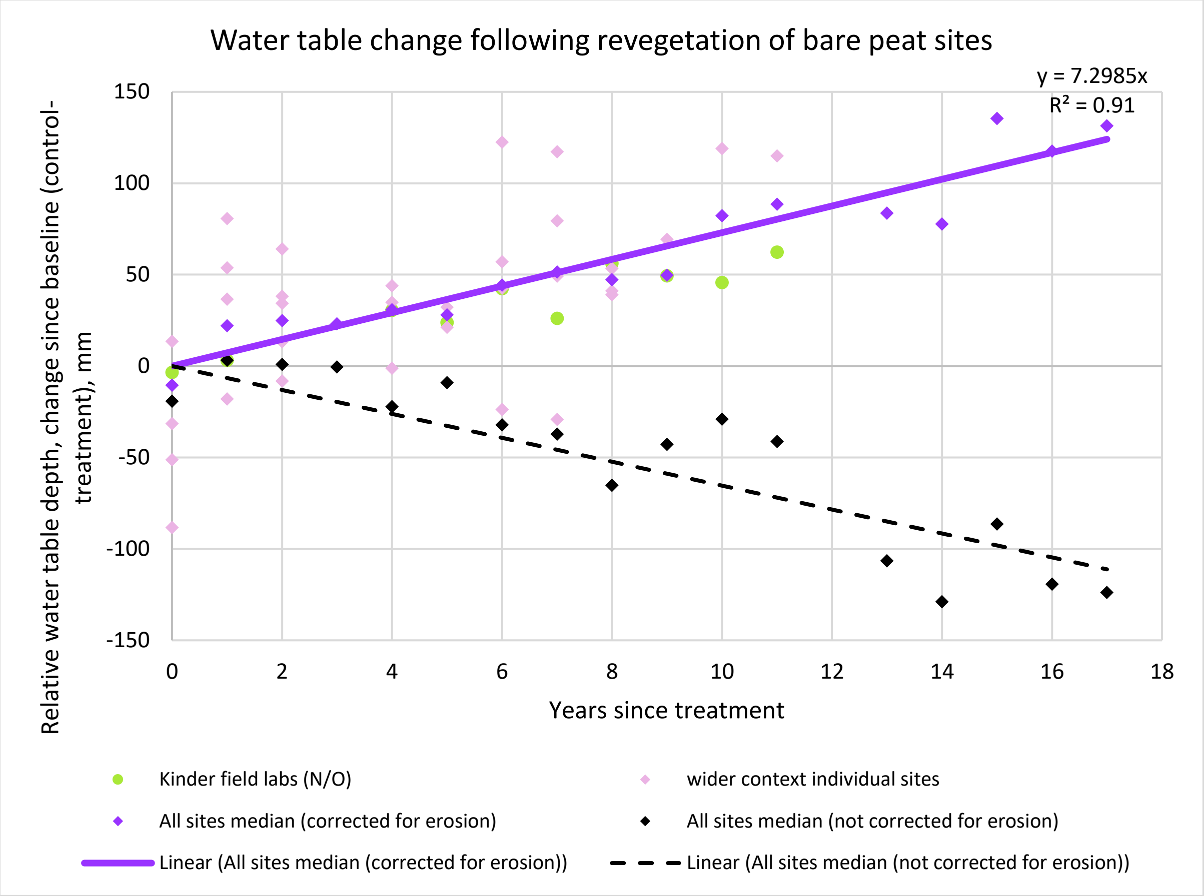

Figure 4: Water table trajectory at wider context treated sites (revegetated only; negligible proximity to gully-blocking or Sphagnum-planting) up to 17 years following initial treatment. Significant erosion at bare peat control sites confounded results and necessitated the correction of data from all sites to compensate for changes in peat surface height

Short-term monitoring of soil moisture using experimental sensors indicated that revegetated sites may be associated with higher near-surface soil moisture than bare peat sites, with revegetated sites maintaining higher soil moisture for longer into dry periods after rainfall (see Figure 5). This effect appeared to be most pronounced in areas of dense *Sphagnum*.

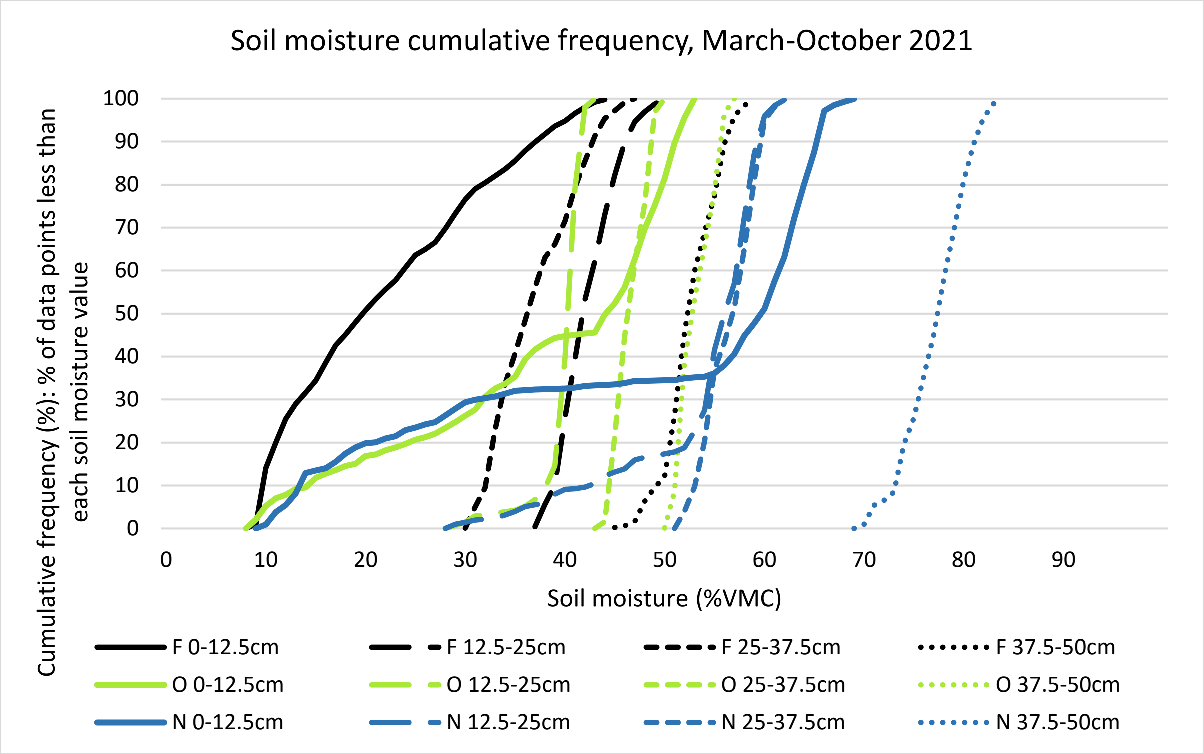

Figure 5: Cumlative frequencies of soil moisture (%VWC) at four depth zones to 50cm at F (bare peat), O (mixed graminoids and bryophytes) and N (dense Sphagnum)

The combined effects of rising water tables and higher soil moisture at restored sites may have important implications for hydrological processes affecting streamflow during storm events:

- **Saturation-excess overland flow generation:** higher water tables and near-surface soil moisture increase the generation of overland flow from saturation-excess
- **Increased overland flow generation:** water on the saturated peat surface must move through the increasingly dense and complex vegetation canopy; this rough surface slows the progress of water to the stream channels (especially where *Sphagnum* is present), attenuating flow in storm events

3.3. Stream discharge

Restoration of bare peat by re-vegetation immediately and significantly altered storm runoff. Storm flow was less flashy, with reductions in peak discharge and increases in lag times. Gully blocking enhanced the benefits of re-vegetation alone. There were no further changes to runoff as the vegetation and gully blocks matured.

The re-introduction of *Sphagnum* mosses provided significant additional benefits of flow attenuation due to increased surface roughness, which increased over time as the *Sphagnum* spread. *Sphagnum* cover of 10–15% was necessary before flow was altered; by the end of monitoring *Sphagnum* cover was estimated to be approaching 25% across the catchment and 85% in the flow pathway network. This resulted in a 65 percentage point (*pp*) reduction in peak discharge (4.2 L s^{-1} ha^{-1}) and a 650 *pp* increase in lag time (160 minutes) – see Figure 6. The changes are ongoing (both in terms of *Sphagnum* growth and flow attenuation) so the end point of the trajectory is unknown.

The observed attenuation of storm flow was maintained in the most extreme events recorded at both treatment mini-catchments, suggesting that the restoration interventions were not overwhelmed in high flow conditions. There was no change in the volume of runoff leaving the system following any of the interventions, indicating that increased surface roughness is the key driver of flow attenuation.

These findings reveal significant NFM benefits at the headwater catchment scale associated with the development of extensive *Sphagnum* cover, especially in riparian zones. While revegetation and gully-blocking have important roles to play in providing NFM benefits, the roughness effect of an extensive and thick *Sphagnum* layer has a significantly greater effect. Modelling suggests that these changes in headwater catchments will results in NFM benefits at the larger catchment scale, including in extreme storm events. Peak flows in flood-relevant events may be reduced by 5–12% in "long-blunt" events and 6–24% in "short-sharp" events (Goudarzi *et al*, in preparation).

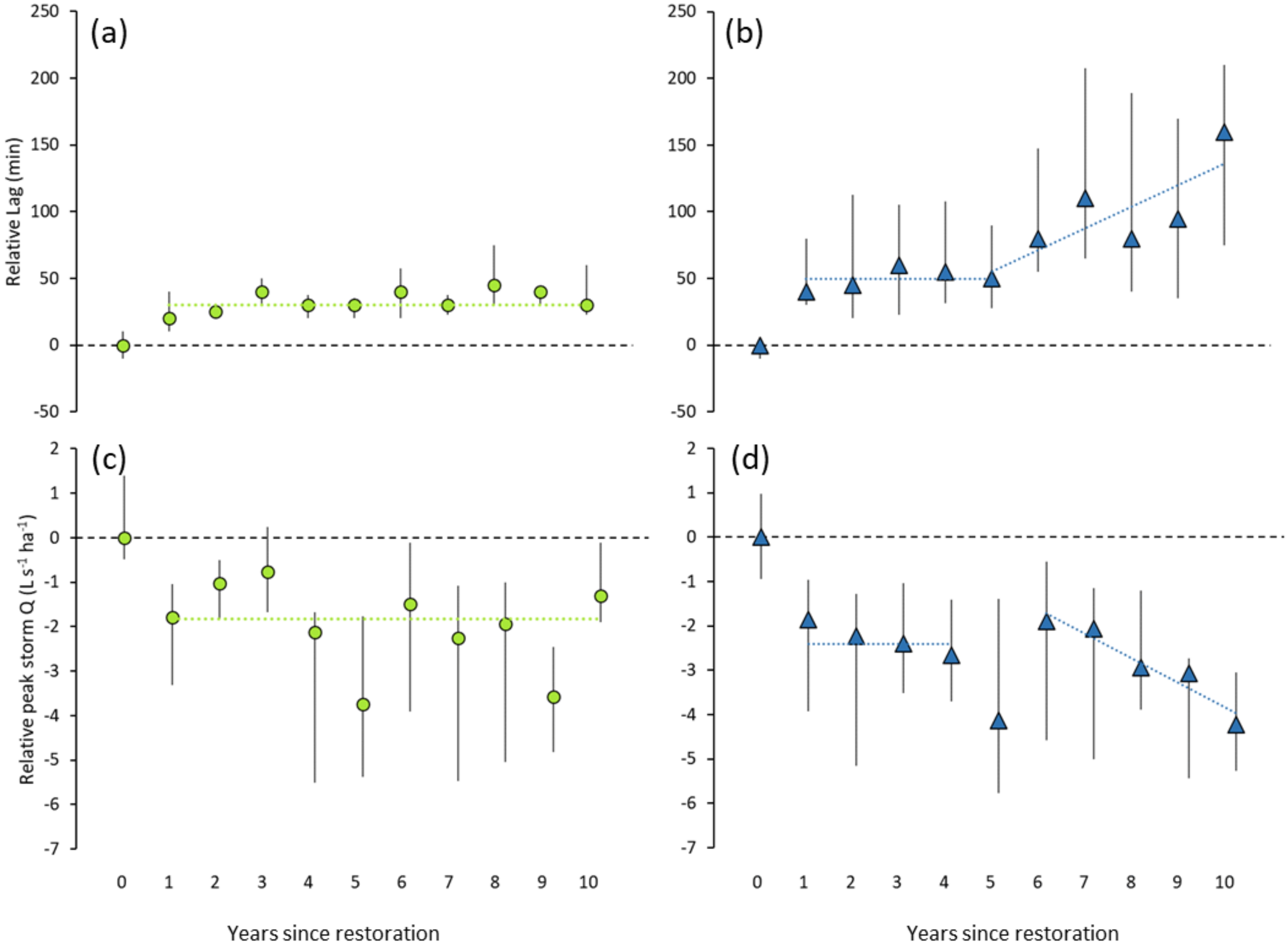

Figure 6: Annual median relative differences between the treatment and control sites for key hydrography metrics: lag time (a and b) and peak discharge (c and d).
Green markers represent site O (revegetation) and blue markers represent site N (revegetation, gully blocking and Sphagnum planting). Statistically significant step changes and trajectories are marked as dotted lines

3.4. Sediment generation and transport

The generation and fluvial transport of sediment and particulate organic carbon (POC) was monitored at the bare peat field lab sites on Kinder Scout. In 2020, ten years after treatment, a 98% reduction in generation/transport of sediment and POC was observed as a result of revegetation alone, and a 99.9% reduction as a result of revegetation, gully blocking and *Sphagnum* planting. This confirmed the findings of Pilkington and Crouch (2015), who reported a 97% reduction in sediment generation/transport at the same sites two years after treatment (see Figure 7). This reduction was likely to have been caused by stabilisation and protection of the peat surface from erosion by the establishment of vegetation cover, which also limited the transport of any mobilised peat.

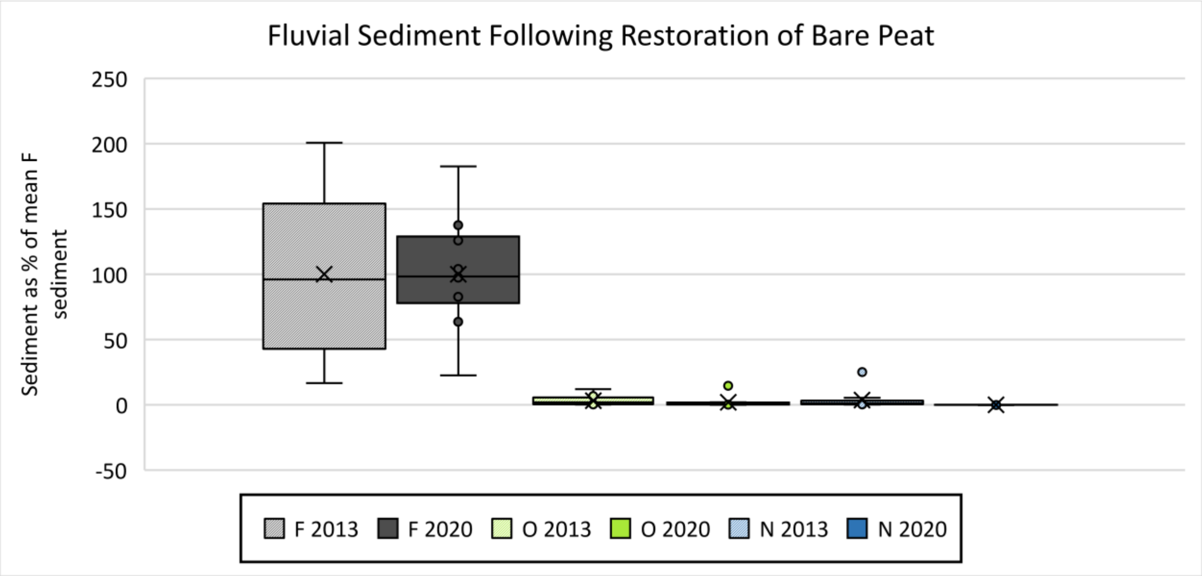

Figure 7: Fluvial sediment collected in TIMS units (short deployment) at F (bare peat), O (revegetation) and N (revegetation, gully-blocks, Sphagnum). Data are presented relative to control (as % of mean sediment collected at F)

3.5. Water chemistry

Application of lime to the restoration sites caused short term spikes in calcium concentration and elevated pH. These chemical shifts were associated with short term reductions in DOC concentration but long-term patterns of DOC concentration and flux were unaffected (see Figure 8). Similarly, calcium concentrations recovered to baseline within 48 months of the final lime application. There was no long-term trajectory of pH associated with the treatment.

The data indicate that the direct chemical impact of the restoration intervention was rapidly flushed from the system and that dissolved carbon fluxes were not significantly modified by the restoration activity beyond an immediate short term impact. It seems likely that water table drawdown associated with the deep gully systems, the morphology of which cannot be fully restored, was a more important control on DOC concentration than surface processes.

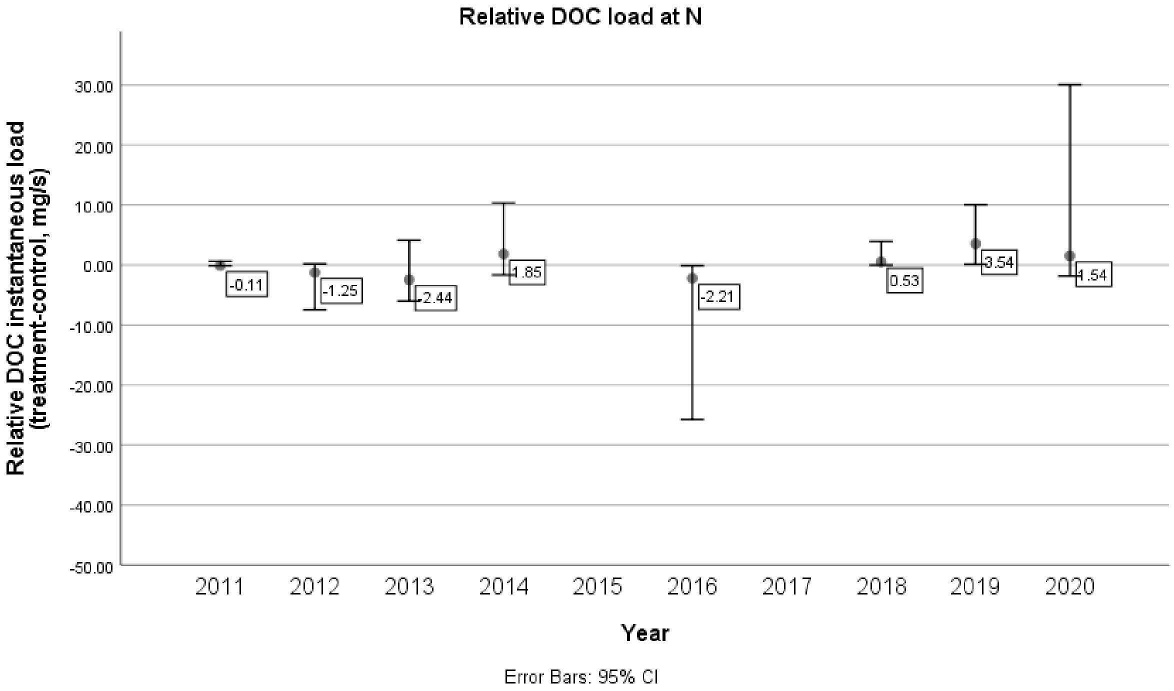

Figure 8: Relative (treatment-control) DOC instantaneous load at N (revegetated, gully-blocked and *Sphagnum*-planted site) showing annual median values and 95% confidence intervals. Positive values indicate higher DOC load at treatment than at control

4. Species dominated sites

The treatment of sites dominated by single vegetation species (*Calluna vulgaris*, *Eriophorum vaginatum* and *Molinia caerulea*) by *Sphagnum* planting, and *Sphagnum* planting plus gully blocking resulted in some changes to ecosystem services being observed in the period up to two years after treatment. These are as summarised in Table 2.

Table 2. Effects of treatment on key variables describing blanket bog ecosystem services; on species dominated sites in first few post-treatment years.

Variable	*Calluna* site	*Eriophorum* site	*Molinia* site
Biodiversity/habitat	Improved	Improved	Improved
Water table	Mixed results	Small rise	Mixed results
Overland flow generation	Increased OFG	No change	Mixed results
Peak storm streamflow	No change	Decreased	No change
Storm streamflow lag time	Increased	No change	No change
Surface run-off	Increased storm start lag time (SphaGB)	No change	No results
Dissolved organic carbon in streamflow	Decreased*	No change	No change
Sediment erosion (and associated carbon emissions)	Not yet known, baseline data collected	N/a	N/a

*significant decrease seen on Spha treatment site; small non-significant increase seen on SphaGB site – the latter possibly due to gully blocking.

4.1. Vegetation diversity

At the species dominated sites, *Sphagnum* was successfully introduced into all the dominant vegetation types: *Eriophorum vaginatum, Calluna vulgaris and Molinia caerulea.* Almost no change in *Sphagnum* cover was recorded in the untreated control areas at all sites. This resulted in a statistically significant increase in cover of *Sphagnum* compared to the untreated control sites, in all cases (Table 3). *Sphagnum* cover showed the largest increase on the *Eriophorum* dominated site, followed by the *Calluna* dominated and increased least on the *Molinia* dominated site.

Table 3. *Sphagnum* cover increases after two years relative to control by dominant vegetation and planting density

Sphagnum cover increase	Dominant vegetation (initial cover)	Plug planting density
53% points	*Eriophorum (67%)*	100 m^{-2}
48% points	*Calluna (GB) (50%)*	100 m^{-2}
22% points	*Calluna (87%)*	100 m^{-2}
11% points	*Molinia (88%)*	100 m^{-2}
10% points	*Eriophorum (54% *conservative estimate)*	4 m^{-2}
05% points	*Calluna (GB) (77%)*	4 m^{-2}
05% points	*Calluna (86%)*	4 m^{-2}
03% points	*Molinia (99%)*	4 m^{-2}

Over the four years of the monitoring, there was little clear change observed in the cover of any of the dominant vegetation types. However, the *Sphagnum* introduction successfully increased the number of indicator species on all sites (Figure 9 Figure 10 Figure 11, Figure 12).

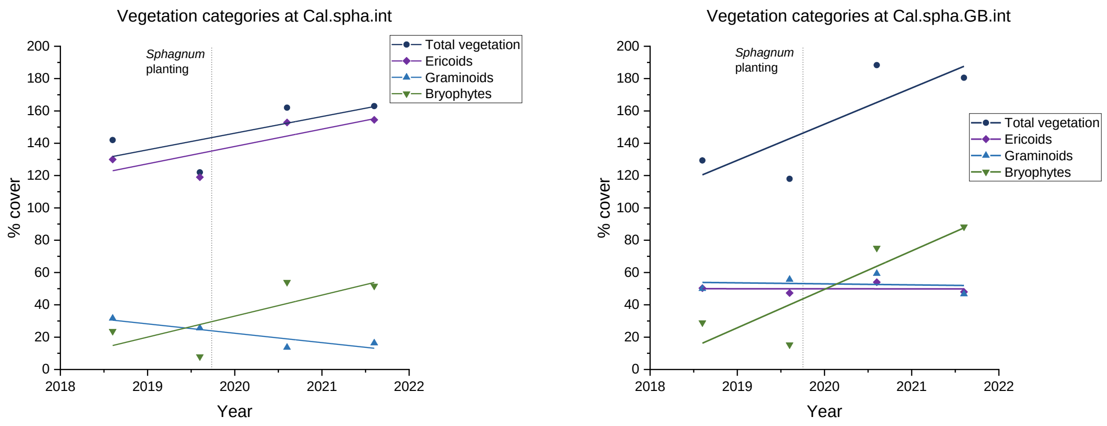

Figure 9. Vegetation category cover at *Calluna* dominated plots planted with high-density Sphagnum plugs

Where *Sphagnum* plugs were planted at a high density into 50% *Calluna vulgaris* cover (in the 'SphaGB intensive plots'), all Common Standards Monitoring criteria for achieving favourable condition were met.

Figure 10. Sphagnum plug growth in *Calluna* site intensive plot (SphaGB.Int.1) on 15/12/2021.

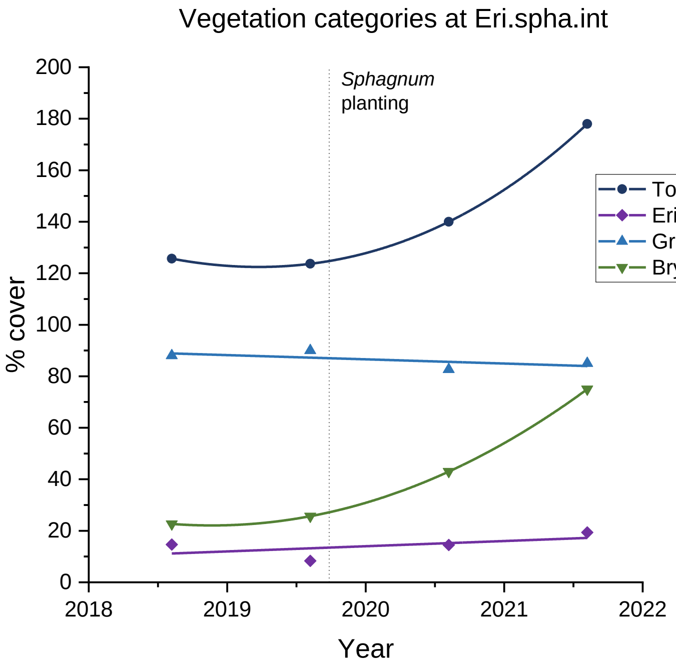

Figure 11. Vegetation category cover at *Eriophorum* dominated plots planted with high-density *Sphagnum* plugs

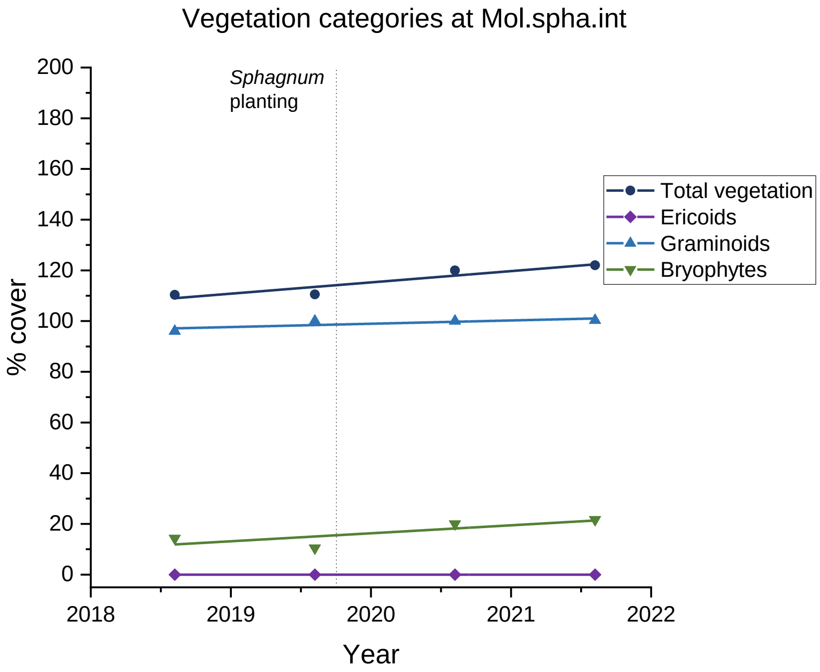

Figure 12. Vegetation category cover at *Molinia* dominated plots planted with high-density *Sphagnum* plugs

On the *Molinia* site, *Molinia caerulea* remained at 85–100% cover on both treatment and control catchments (being consistently higher on the treatment catchment both before and after treatment), and where *Sphagnum* was introduced at different planting densities. There was no clear change observed over the monitoring period.

4.2. Water table

Monitoring of water tables at species dominated sites produced some signs that water tables may be changing following treatment with *Sphagnum* moss inoculation, although there was variability between sites. The short post-treatment monitoring period (one year for intensively planted plots and two years for the rest of the sites) meant that it was difficult to draw firm conclusions or identify trends. This serves to highlight the importance of continued monitoring over a longer period.

At the *Calluna* dominated site, manual water table measurements showed no statistically significant differences ($p < 0.05$) in treatment sites relative to the control site, in either intensively planted plots (rises in median water table of 27 mm Spha; 35 mm SphaGB as seen in Figure 13) or the wider site (small drop of 15 mm Spha; 8 mm SphaGB).

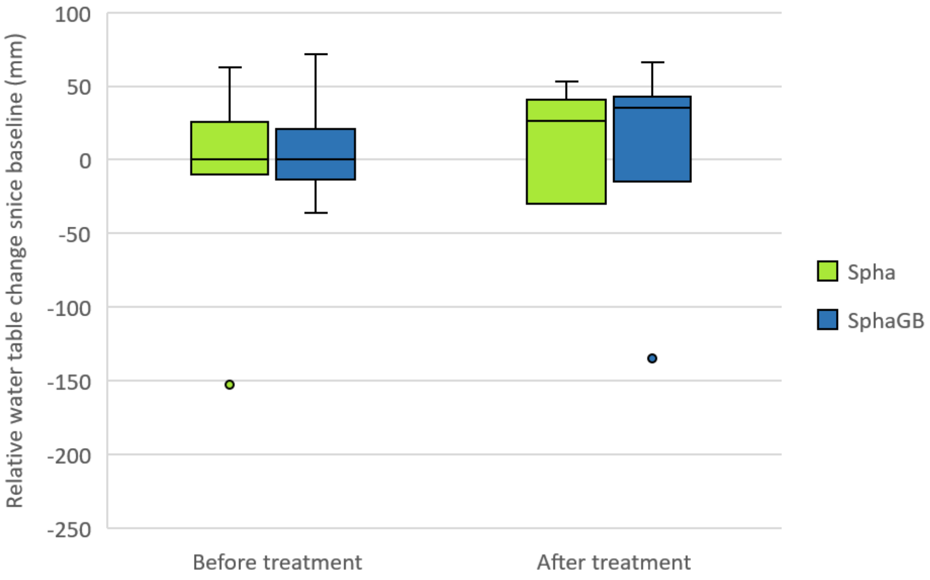

Figure 13. Boxplots of mean manually measured water table depth (mm) in treatment catchment intensive plot dipwells on *Calluna* site, relative to control (control – treatment), before and after treatment.

However, continuous data collected from the same intensive plots on the *Calluna* site suggested a marginal although significant lowering of water table relative to control on the SphaGB plot and a slight but significant raise in water table relative to control on the Spha plot. The initial results from this site are somewhat unclear due to the small changes detected, and the short monitoring period. Longer term monitoring will be greatly beneficial in understanding any changes taking place at the site.

At the *Eriophorum* dominated site manual water table measurements showed little change in the wider treatment site relative to control, but a small significant ($p= 0.031$) rise in median water table of 18 mm was observed in the intensive plots (Figure 14) where *Sphagnum* was planted at 100 plugs m^{-1}. These plots had experienced the greatest increase in *Sphagnum* cover of all the dominant vegetation types monitored (see section 4.1 above). A similar change was observed in the continuous water table record where daily median water tables showed a small but significant rise of 13.8 mm relative to control. Analysis of residence times also suggests that the water table spent a higher proportion of the time nearer the surface relative to control as a result of *Sphagnum* treatment. The observed changes are suggestive of a trend of rising water table, but continued monitoring will be essential to provide further evidence.

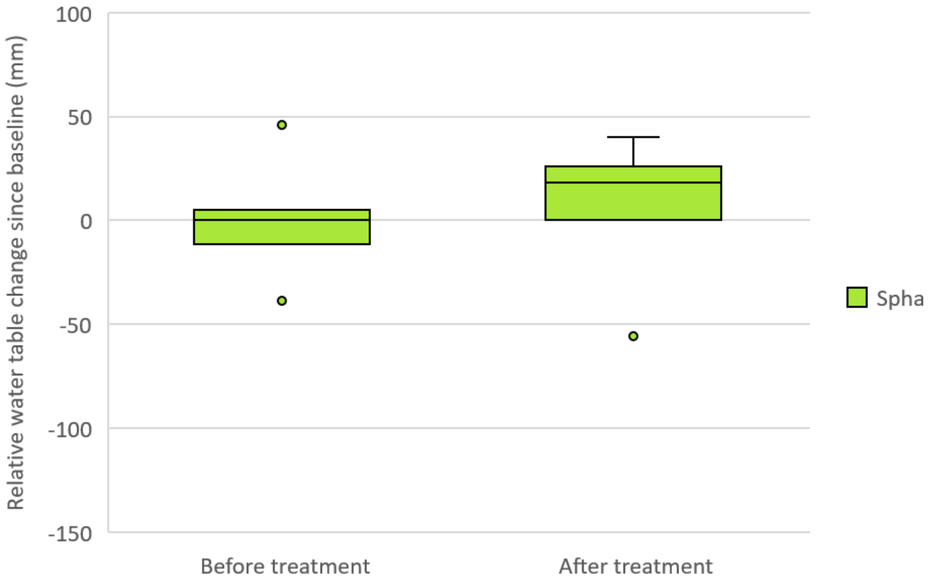

Figure 14. Boxplots of mean manually measured water table depth (mm) in treatment catchment intensive plot dipwells on *Eriophorum* site, relative to control (control – treatment), before and after treatment.

At the *Molinia* dominated site, manual water table measurements at the intensive plots showed a small but statistically insignificant fall in water table of 12 mm relative to control. Continuous dipwell data from the intensive plots corroborated the manual measurements, showing a small but significant fall in water table of 20 mm relative to control. In contrast, the wider site dipwell cluster measurements showed a small but statistically significant (p = 0.043) median rise in water table of 18 mm relative to control (Figure 15). However, it is important to note that the generally shallower median values of the treated plot meant there was diminished potential to reduce depth to water table compared to the deeper control – thus given equal forcing the control would likely provide a greater reduction.

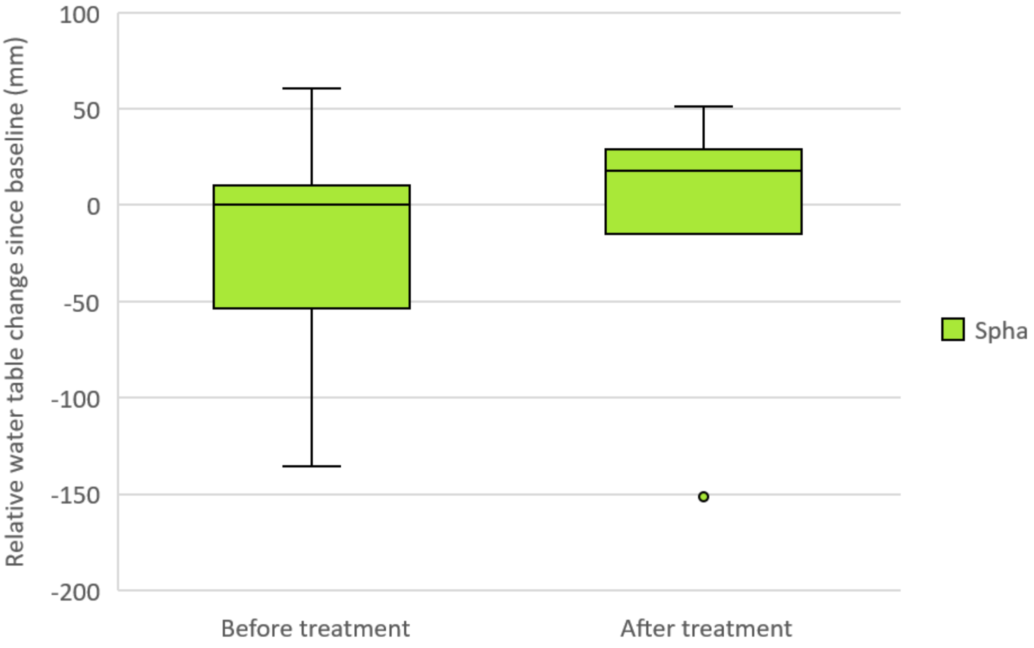

Figure 15. Boxplots of mean manually measured water table depth (mm) in treatment catchment cluster on *Molinia* site, relative to control (control – treatment), before and after treatment.

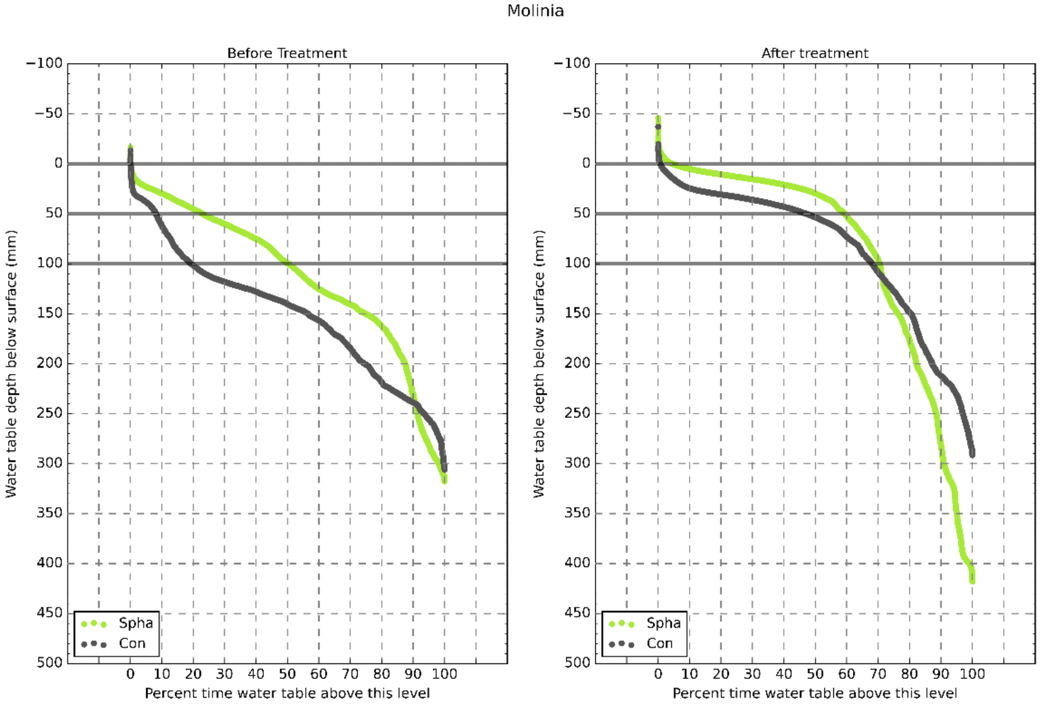

Figure 16. Water table residence time curves for *Molinia* site. Residence time curves for each dipwell based on 5 minute sampling intervals. Curves display the percentage of time a water table exists above a certain water table level.

Analysis of residence times (Figure 16) showed that the relative percentage of time above 0 mm became more negative (control minus treatment) indicating a relative increase of above surface water at *Sphagnum* treated plot in the after-treatment year. Relative percentage above 50 mm remains similar, whereas relative percentage above 100 mm becomes substantially less negative indicating a substantial increase in percentage of time above 100 mm at the control, alongside a more subdued response at the *Sphagnum* treated plot. As water tables become shallower the potential for a high magnitude change to shallower water tables is reduced as the surface is approached. The *Sphagnum* treated plot was already at a relatively high percentage for this level in year 0, which would reduce its potential magnitude of response in comparison to the control.

4.3. Overland flow generation

Flow on a peatland surface is generated either by, or as a combination of, a surface of low permeability retarding infiltration or by high water tables effectively providing the former. Evidence here is confined to presence or absence of water. Crest-stage runoff traps were used to monitor surface ponding, with the intention of evidencing the potential for the generation of overland flow.

The higher rainfall in the 'after' treatment period for both mini catchments and intensive plots mean all control and treated locations recorded an increase in overland flow. No significant lags in water table responses have been observed from the continuous records from the *Molinia* and *Eriophorum* plots despite substantial increases in *Sphagnum* cover – suggesting that any flow attenuation has not affected the water tables below thus far. Although, spreading laterally, the planted *Sphagnum* has not had sufficient time to attain any depth to substantially affect surface roughness.

On the *Calluna* site, the treated catchments showed a greater increase in overland flow generation from the before to the after periods, compared to control.

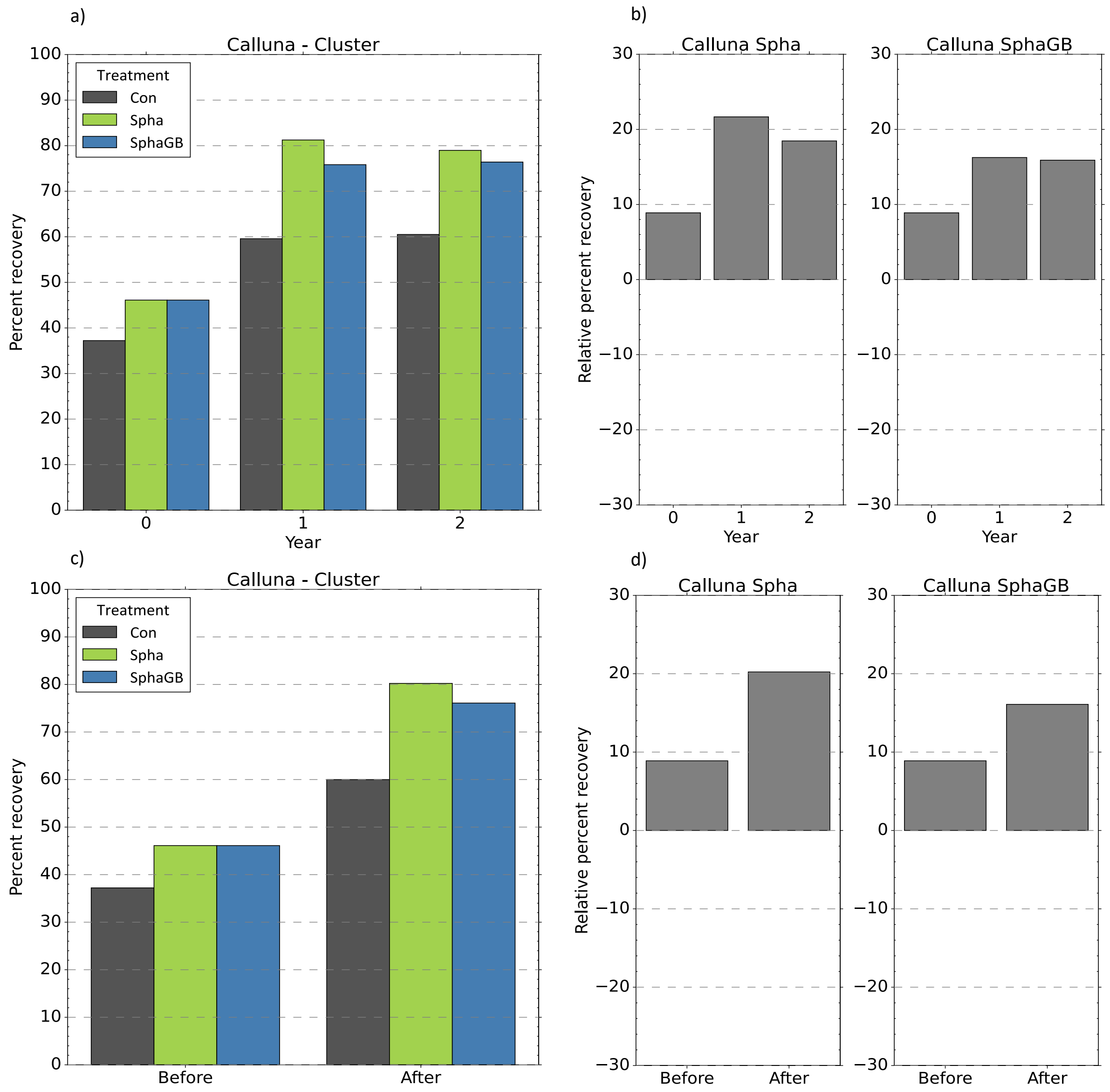

Figure 17. Crest stage tube percentage recovery at each mini-catchment cluster on *Calluna* site. Cluster crest stage tube a) percentage recovery at each treatment and b) difference between treatment and control for each year of project at the *Calluna* dominated sites. Figures c and d show the same data represented as before and after treatment.

On the *Eriophorum* site, little change was seen in overland flow relative to control, but this lack of change was consistent with relatively stable water table from before to after treatment periods on this site.

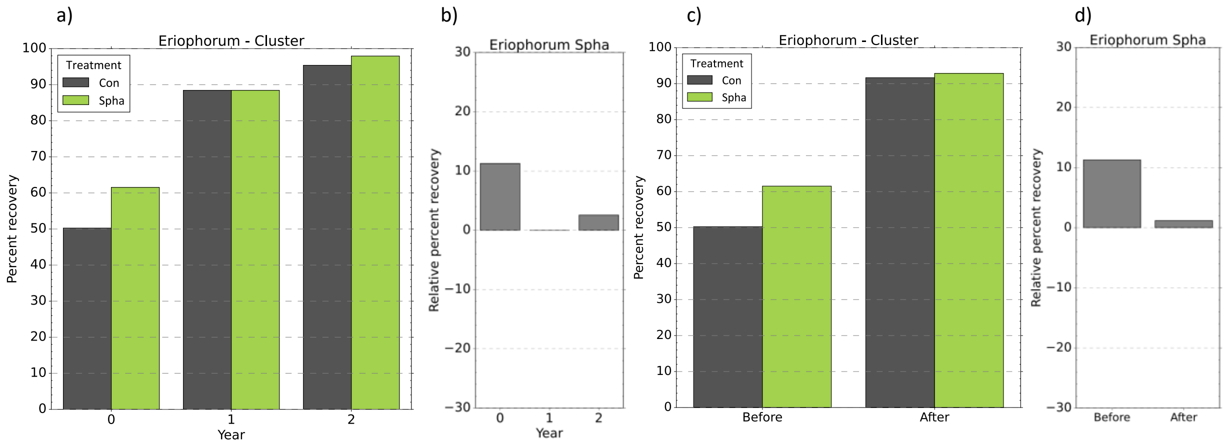

Figure 18. Crest stage tube percentage recovery at each mini-catchment cluster on *Eriophorum* site. Cluster crest stage tube a) percentage recovery at each treatment and b) difference between treatment and control for each year of project at the *Eriophorum* dominated sites. Figures c and d show the same data represented as before and after treatment.

On the *Molinia* site a small relative increase in overland flow of 5% was seen in the lower planting density areas, whereas a small relative reduction in overland flow of ~18% was found in the high density planning areas. These observations should be treated with caution when remarking on the effects of *Sphagnum* due to the short time period since planting. It is essential to continue monitoring to observe changes in both overland flow and water table over a much longer period firstly to allow *Sphagnum* to gain greater coverage and depth but also to observe reactions to various climate conditions.

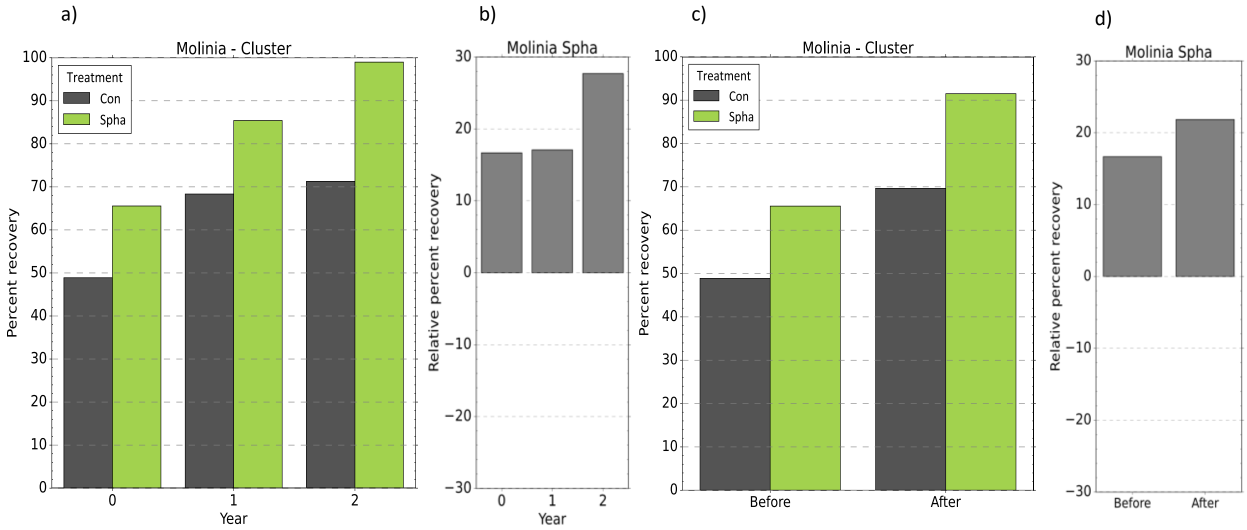

Figure 19. Crest stage tube percentage recovery at each mini-catchment cluster on *Molinia* site. Cluster crest stage tube a) percentage recovery at each treatment and b) difference between treatment and control for each year of project at the *Molinia* dominated sites. Figures c and d show the same data represented as before and after treatment.

4.4. Stream discharge

At the *Calluna* dominated site no statistically significant difference in relative peak discharge was observed at either treatment plots after treatment. The difference from control was similar for both treatment plots suggesting that gully blocking was did not have a significant effect (Figure 20).

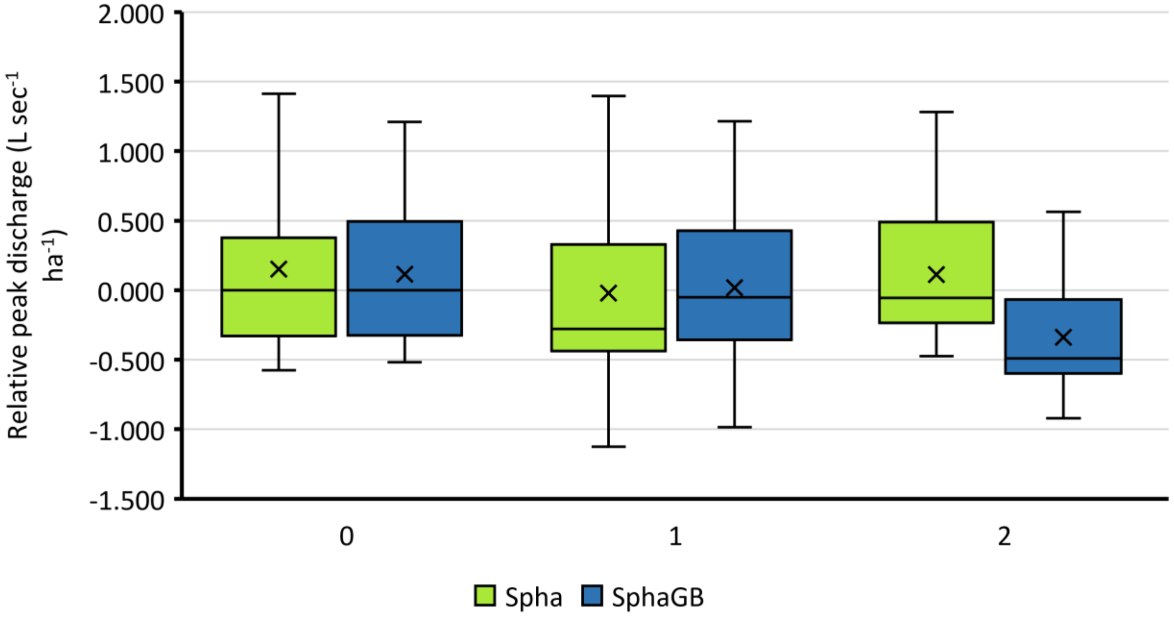

Figure 20. *Calluna* site peak discharge (relative to the Con mini-catchment) for Spha and SphaGB in each BACI year. Year 0 median value has been normalised to zero to show change since treatment.

However, on both sites the relative peak lag time became significantly longer in the post-treatment period. Comparing both sites suggest that gully blocking had more effect on peak lag than *Sphagnum* planting alone during these early post-treatment years. Both sites also saw a significant decrease in relative run-off co-efficient after treatment, suggestive of Sphagnum increasing the holding capacity of the catchment. No difference was found in the Hydrograph Storm Index.

At the *Eriophorum* site, relative peak discharge was significantly reduced (median of ~0.5 litres per second per hectare) at the *Sphagnum* treatment weir in both years 1 and 2 post-treatment (Figure 21).

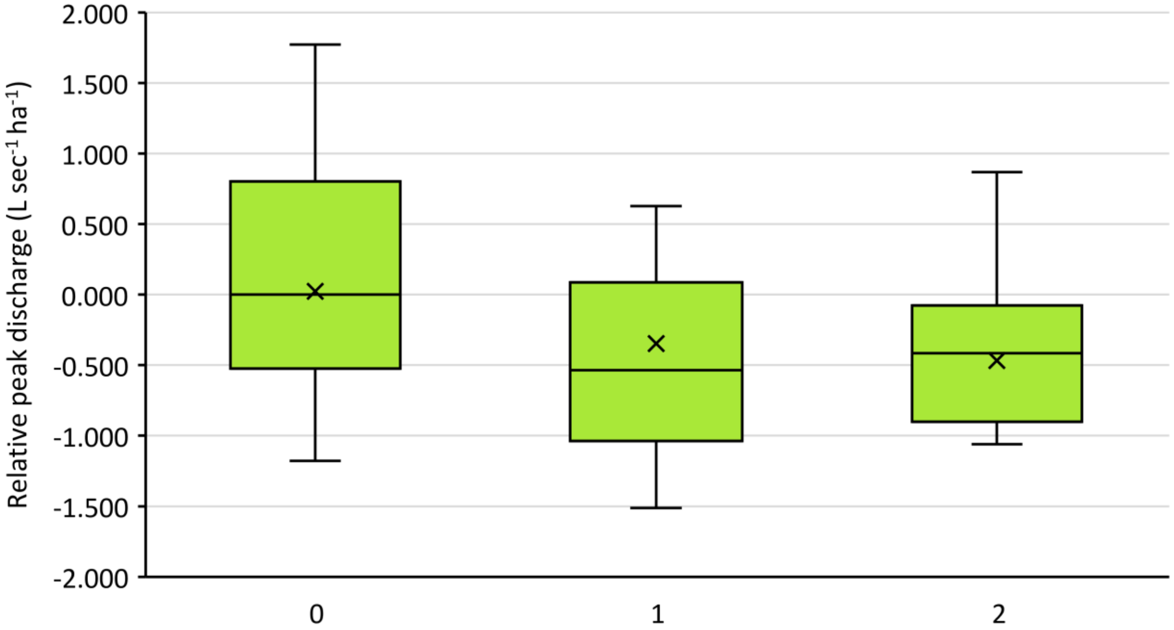

Figure 21. ***Eriophorum*** **site peak discharge (relative to the Con mini-catchment) for Spha each BACI year. Year 0 median value has been normalised to zero to show change since treatment.**

The relative peak lag time at the treatment catchment was longer post-treatment, but not significantly. Run-off co-efficient results were unclear, due to the possible influence of confounding factors – however no significant changes were found. The relative Hydrograph Storm Index at the treatment plot was also lower in years 1 and 2 post-treatment, albeit this not a significant result.

At the *Molinia* site, no significant change was found in relative peak discharge at the treatment catchment in the post-treatment years (Figure 22).

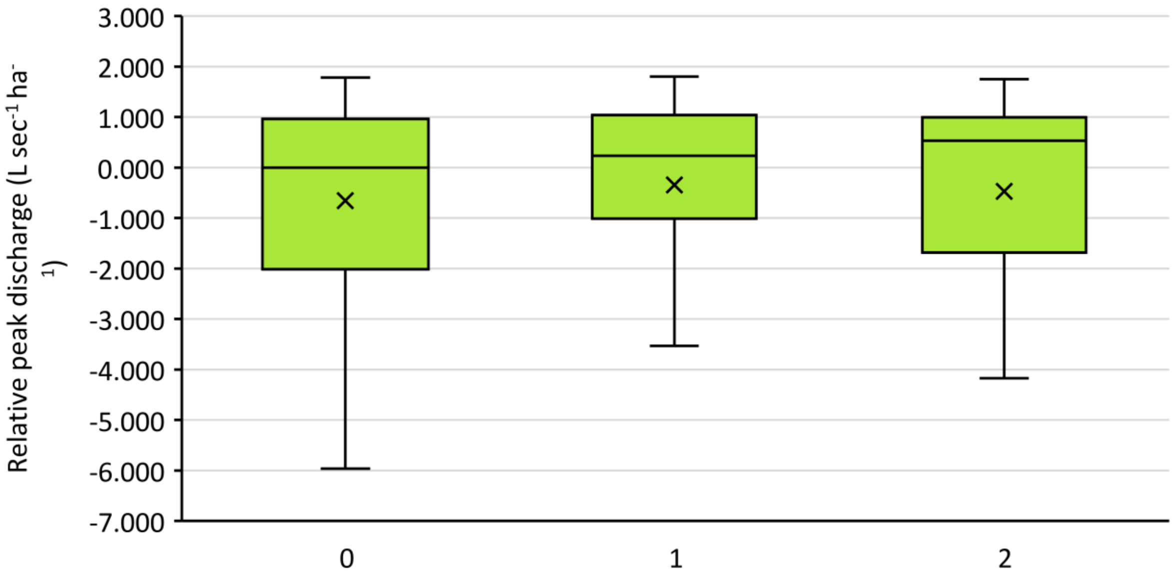

Figure 22. ***Molinia*** **site peak discharge (relative to the Con mini-catchment) for Spha each BACI year. Year 0 median value has been normalised to zero to show change since treatment.**

There were very small differences found between peak lag time in each catchment. The relative difference was not significant. There were quite clear differences in the runoff-co-efficient between the control and treatment catchments both before and after treatment. Relative to control, run-off co-efficient at the *Sphagnum* site was similar before and after planting. There was no clear trajectory in the relative runoff percentage after intervention. Relative to control, the Hydrograph Storm Index was not significantly different at the treatment catchment after planting.

It should be noted that for the majority of results on all sites, the effect size was small, variable and within error, so that while some results are showing the beginning of a trend, the effect of *Sphagnum* and/or gully blocking on storm hydrology metrics is small so far.

4.5. Surface run-off

To complement the monitoring of overland flow generation, the characteristics of surface run-off (overland flow) on the species dominated sites were detected using ‘run-off plots’, sometimes also referred to in this report as ‘intensive plots’. These comprised of a plastic gutter with one side inserted horizontally into the peat surface below the plot. Water that flowed over the ground surface within the plot was diverted into a tipping bucket rain gauge.

However, due to operational issues associated with monitoring remote field locations, there were periods where no data were collected for some sites, resulting in gaps in the record. Issues were most apparent at the *Molinia* dominated sites where no useable data were recovered. This meant that analysis was limited to peak and start lag times during storm events on the *Calluna* and *Eriophorum* sites.

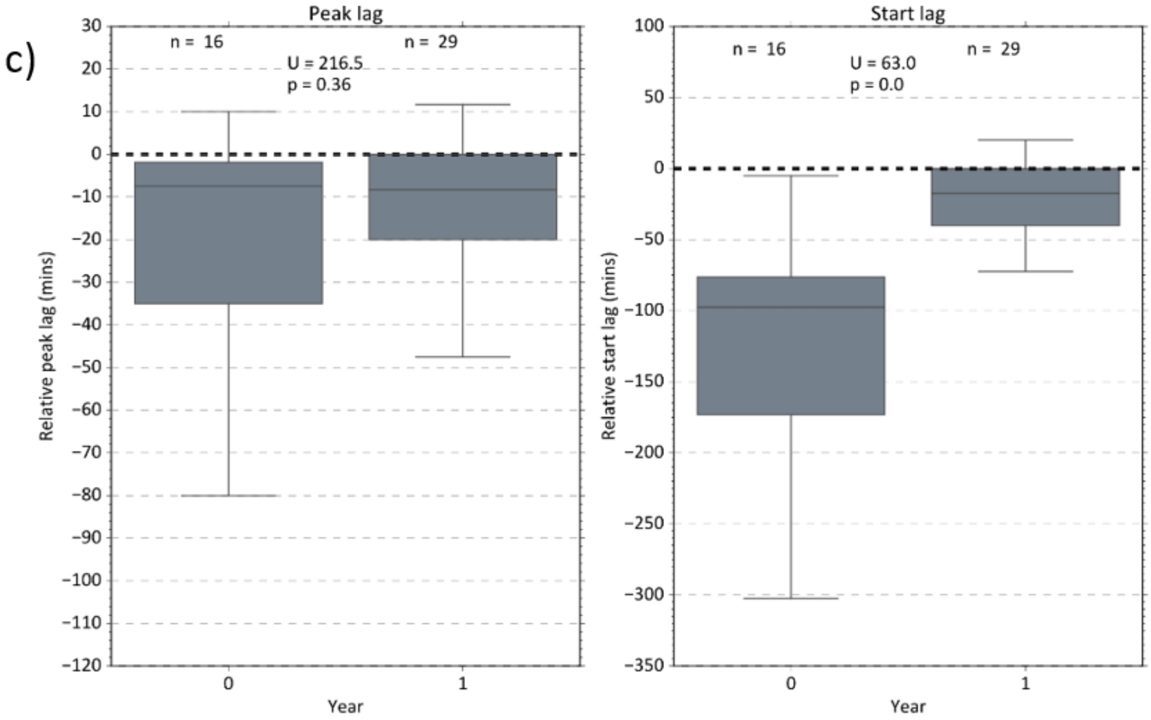

Figure 23. ***Calluna*** **SphaGB run-off – relative median start and peak lags to rainfall for each project year. Mann-Whitney U significance tests are displayed for differences between year 0 and 1**

On the *Calluna Sphagnum* treated site (Spha), no significant changes were detected in relative start or peak lag times during the monitoring period. However, the plots in the *Sphagnum* and gully-blocked treatment catchment (SphaGB) did show a substantial and significant increase in start lag time relative to control, as seen in Figure 23. This change appears to be unrelated to unequal seasonal representation between years, or to be the result of gully blocking – due to the location of the plots. However, the SphaGB plots did experience a larger and more rapid increase in *Sphagnum* cover compared to the Spha plots (see 4.1 above).

On the *Eriophorum* site there was little change in relative median start or peak lag values from before to after treatment years (Figure 24) suggesting that both have maintained the same relative behavior with no clear changes due to treatment.

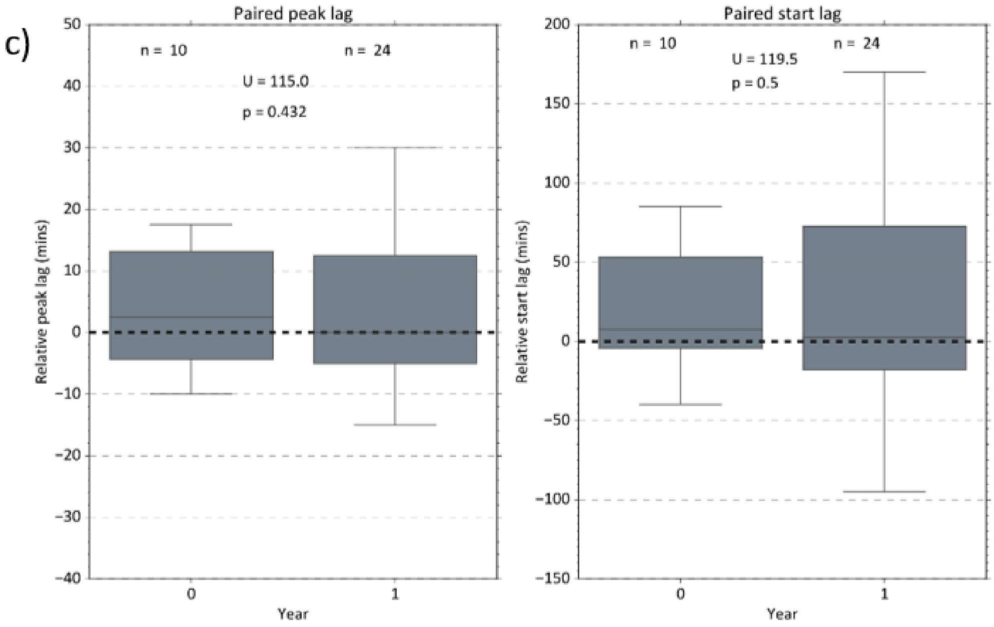

Figure 24. *Eriophorum* Spha run-off – relative median start and peak lags to rainfall for each project year. Mann-Whitney U significance tests are displayed for differences between year 0 and 1

4.6. Sediment generation and transport

Monitoring at the *Calluna*-dominated site was carried out one year after treatment (*Sphagnum*-planting; *Sphagnum*-planting and gully-blocking), to establish a baseline (Figure 25) with which to compare future results in the longer term. Given that the planted *Sphagnum* mosses had not yet established a large coverage within the catchment, it is unlikely that they would have an observable impact on sediment generation and transport within the catchment. Differences in results between the catchments were therefore more likely due to differences in sediment source availability, connectivity of the drainage network and vegetation conditions within the flow pathways. Estimates for bare peat and vegetation cover within each gully monitored were made using aerial imagery and ground-truthing to aid interpretation of results and future analysis.

The results shown below should be considered as a baseline against which to monitor any future changes as the *Sphagnum* mosses establish across the catchments.

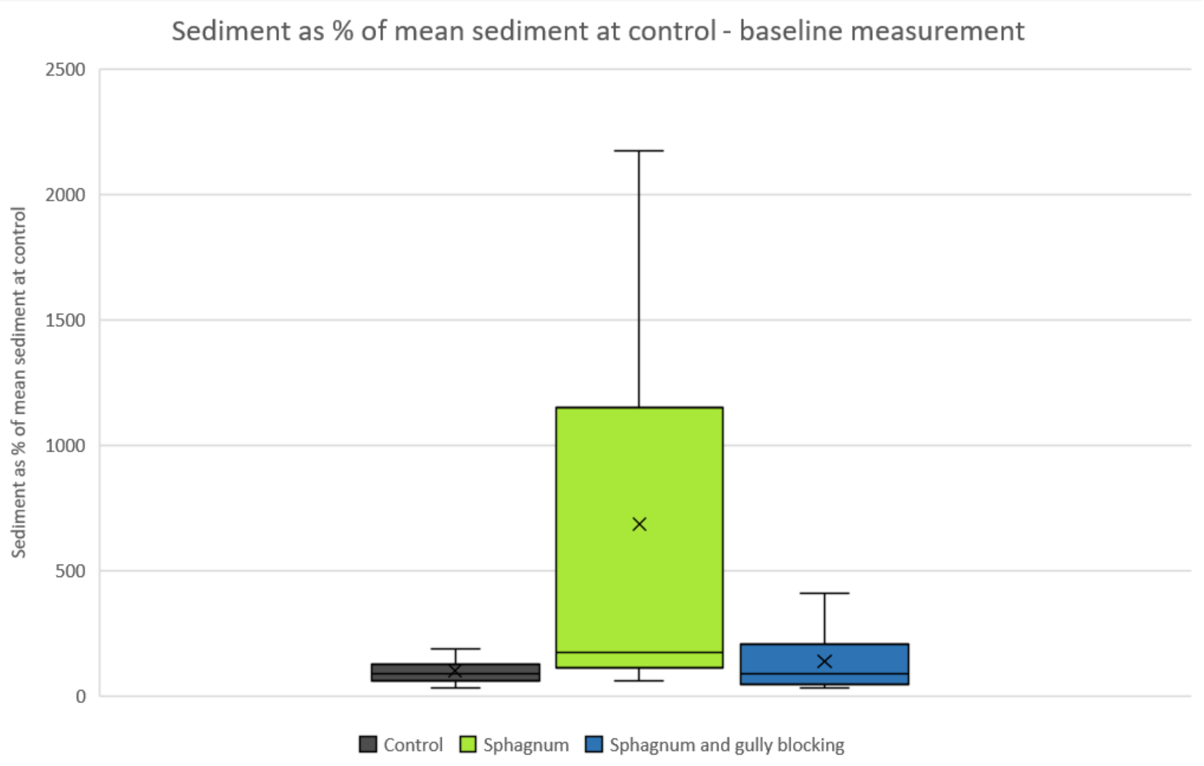

Figure 25. Boxplots displaying distribution of sediment mass collected from the ten TIMS units deployed in each Calluna mini-catchment, as a percentage of the mean sediment mass collected in the control mini-catchment.

4.7. Water chemistry

As summarised in Table 4 below, the data suggest that where *Sphagnum* was introduced to sites dominated by single species (*Calluna vulgaris*, *Eriophorum vaginatum* and *Molinia caerulea)* it had some possible impacts on chemistry of water leaving the catchments. Electrical conductivity (EC) decreased on the *Molinia* site and DOC concentrations decreased on the *Calluna* site. Planting *Sphagnum* did not change the pH, however.

Gully blocking on the *Calluna* site 'SphaGB' catchment had no statistically significant effect on the EC and DOC concentration, or character of DOC (E4:E6 and $SUVA_{254}$). It did not change the pH of the water leaving the catchments.

Planting *Sphagnum* at lower densities (4 plugs m^{-2}) has the potential to decrease DOC concentrations in overland flow and soil solution. The DOC concentration decreased consistently in all four intervention catchments after low density *Sphagnum* planting, however only some of these findings were statistically significant.

Planting *Sphagnum* at high densities (100 plugs m^{-2}) has the potential to decrease DOC concentrations in overland flow and soil solution. At some sites, there were decreases in DOC concentrations in overland flow, and soil solution. However, some sites had increased DOC concentrations in overland flow, and soil solution, and some sites had no change. Most of the results were not statistically significant.

The DOC flux from *Calluna* and *Molinia* catchments appeared to be decreased by planting *Sphagnum*, but conversely there was found to be no clear change in DOC flux after planting in *Eriophorum* catchment.

It will be important to repeat monitoring of these variables in the future in order to increase certainty about these effects.

Table 4. Summary of the direction of change in DOC concentration, pH, EC, SUVA254 and E4:E6 at Calluna (CAL), Eriophorum (ERI) and Molinia (MOL) sites.
Arrows show the direction of change. One-way Mann-Whitney U test results are shown with: NS = not significant; * = $p < 0.05$; ** $p < 0.01$; and *** $p < 0.001$.

Vegetation	**Location**	**Impact of treatment**	**Direction of change after catchment intervention**				
			pH	**EC**	**DOC**	**E4:E6**	**SUVA$_{254}$**
CAL	Weir	Spha (Spha – Con)	- NS	↓ NS	↓ *	↑ NS	↑ NS
CAL	Weir	GB (SphaGB – Spha)	- NS	↑ NS	↑ NS	↑ NS	↓ NS
CAL	Weir	Spha&GB (SphaGB – Con)	- NS	↓ NS	↓ NS	↑ NS	- NS
ERI	Weir	Spha (Spha – Con)	- NS	↓ NS	↓ NS	- NS	↓ NS
MOL	Weir	Spha (Spha – Con)	- NS	↓ *	↓ NS	↓ NS	↓ NS

5. References

Alderson, DM, Evans, MG, Shuttleworth, EL, Pilkington, M, Spencer, T, Walker, J & Allott, TEH (2019). 'Trajectories of ecosystem change in restored blanket peatlands', *Science of the Total Environment*, vol. 665, pp. 785–796. https://doi.org/10.1016/j.scitotenv.2019.02.095

Goudarzi, S., Milledge, D., Holden, J., Allott, T., Evans, M., Shuttleworth, E., Johnston, A., Edokpa, D., Kay, M., Spencer, T. (in preparation for publication). 'Natural Flood Management through peatland restoration: catchment-scale modelling of past and future scenarios in Glossop, UK'

Funded by the EU LIFE programme and co-financed by Severn Trent Water, Yorkshire Water and United Utilities. With advice and regulation from Natural England and the Environment Agency, and local advice from landowners.

Moors for the Future Partnership
The Moorland Centre, Edale, Hope Valley, Derbyshire, S33 7ZA
E: moors@peakdistrict.gov.uk
W: www.moorsforthefuture.org.uk