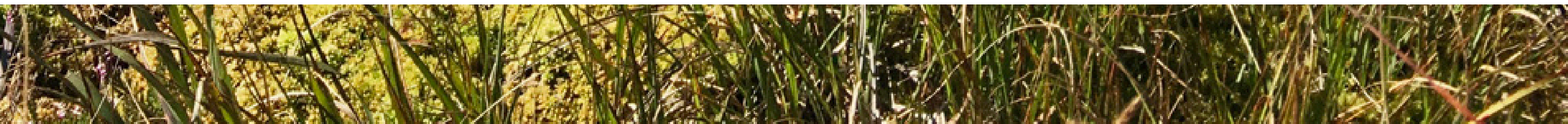
MIRES ON THE MOORS

Science and Evidence Report 2020

Environment Agency

UNIVERSITY OF EXETER

South West Water



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Thanks are also due to the previous members of the University of Exeter research team, the South West Peatland Partnership, and the numerous volunteers that have been involved with the delivery of the project.

Mires On The Moors Project

Science and Evidence Report 2020

South West Water's Upstream Thinking Programme, working with a multitude of stakeholders, has restored a total of 24.8 km^2 (2480 ha) of peatland across Exmoor and Dartmoor since 2010 as it became apparent that much of the peatlands we rely on for vital ecosystem services were in a degraded and worsening state. Research has been central to the restoration programme; to better understand the current state of these peatlands, design appropriate restoration plans and evaluate the success of restoration, our findings are outlined within this report.

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Foreword and Introduction to this Report

The degraded state of UK peatlands has been recognised as a critical problem that should be tackled with some urgency if the UK is to meet its targets of carbon storage and Greenhouse Gas Removal. The South West peatlands of Dartmoor, Exmoor and Bodmin Moor are potentially huge carbon stores, with equal potential to store water at times of heavy rainfall and release cleaner water during times of drought. However, over a decade ago, pilot work funded by South West Water identified that these peatlands were heavily modified – due to drainage for agricultural purposes, removal of peat for fuel, historical overgrazing and practices such as burning or moorland swaling to regenerate vegetation for grazing. Consequently, research began in 2010 to understand the way in which the South West peatlands are structured, how they function and furthermore how they might respond to restoration practices which could restore some of the 'natural' functioning of these degraded ecosystems. In addition, given their southerly location, it was hypothesised that these peatlands may be the first in the UK to respond to changes in climate and thus could be 'canaries in the coalmine' to educate us about how the more extensive, northerly peatlands might respond in decades to come.

The following report describes the outcomes of the last 5 years of research into peatland restoration. The report is supplemented by a number of peer-reviewed scientific papers which are appendicised and will be updated as more of the research is published in years to come. These reports and papers can be found here: **www.exeter.ac.uk/creww/research/casestudies/miresproject**

Ongoing work over the next 5 years will continue to monitor the structure and function of South West peatlands, building on the short-term, post-restoration story told here, to develop understanding of how peatlands can provide a wide range of ecosystem services to society, if they are managed in an environmentally progressive manner, which considers all users and beneficiaries of these common resources.

Richard Brazier

Professor of Earth Surface Processes and Director of the Centre for Resilience in Environment, Water and Waste.

EXECUTIVE SUMMARY

- Up to January 2020, 27.8 km^2 (2780 ha) of peatland have been restored following methods specifically developed for Exmoor and Dartmoor. **Page 12.**
- In shallow peats, water table responses to restoration are complex. In the driest areas, where drainage had the greatest effect pre-restoration, water tables rose by as much as 4 cm. Overall, however, water tables remain statistically similar post-restoration. **Page 16.**
- In deeper peats, restoration increased the permanent deep water storage in the soil by 7.3 cm and increased average water tables by 2.45 cm. **Page 20.**
- Restoration can significantly alter rainfall runoff regimes in restored catchments; within deeper peat, gully flow was reduced by around 66 %. In shallow peatlands the flow response was more complex with storm generated discharge reduced by up to 32 % in some catchments. **Pages 16 and 20.**
- In shallow peats, restoration has not significantly changed water quality, suggesting that there has not been a significant change in the ecohydrological function of the peatland to-date. **Page 24.**
- Post-restoration, the total load of dissolved organic carbon leaving the study site on Dartmoor during storm events was approximately 1/3 of the pre-restoration loads due to a significant decrease in runoff. **Page 28.**
- Population densities of the sheep tick, a vector of economically important livestock diseases, are significantly lower in mires than in drier habitats on the same sites. **Page 32.**
- Bog asphodel (*Narthecium ossifragum*), a potentially toxic plant, contributes up to 20 % forage value in a transitional bog community and continues to survive but has not spread significantly post-restoration. **Page 34.**
- In shallow peats, restoration did not significantly alter (heterotrophic) respiration of the peat soil or increase methane fluxes (even after 7 years), illustrating how degraded these peatlands were and how much intervention is required to restore ecosystem functionality. **Page 35 and 36.**
- In deeper peats, raised water tables significantly reduced (heterotrophic) respiration of the peat store and initially increased methane emissions; both processes are indicative of a return to more natural functioning in the longer term. **Page 40.**
- Dartmoor National Park is estimated to have 158 ±101 km^2 (15800 ha) of peat >0.4 m deep storing 13.1 megatonnes of carbon. **Page 42.**
- Functionally intact blanket bog covers just 3.6 km^2 (360 ha) of Dartmoor, however it is fragmented and often surrounded by ecohydrologically degraded peat which covers an area of 29 km^2 (2900 ha). **Page 42.**

BACKGROUND AND CONTEXT

Typical peatland vegetation in the South West of England underlain by a carpet of *Sphagnum* mosses.

Adder (*Vipera berus*) sunning itself on Exmoor.

Peatlands are now recognised nationally and internationally as providing many essential and valuable ecosystem services; they play an important role in water management, act as carbon stores, preserve archaeology, and are rare and important habitats with unique flora and fauna[1]. In 2011, the IUCN identified these landscapes as the single most important terrestrial carbon store in the UK and that around 70 % of all UK drinking water comes from upland, peatland catchments[2].

Peatlands form where waterlogged conditions limit decomposition to such an extent that dead vegetation accumulates as peat soil. The uplands of the South West have a specific type of peatland called blanket bog which develop in cool and wet conditions, forming predominately from *Sphagnum* mosses. Although blanket bog is extensive across the moors of the South West, it is globally rare, consequently these areas are internationally important ecosystems, with many designated as Sites of Special Scientific Interest and/or Special Areas of Conservation.

Peat accumulates slowly, mm's-cm's per year over thousands of years. These gradually accumulated deposits hold a precious record of past climate, land use and ecology as well as preserving rare organic archaeological remains such as the Whitehorse Hill cist. They also store huge amounts of carbon which, if not safeguarded, could be released into the atmosphere worsening the climate emergency or washed into rivers which rise upon the moors reducing water quality downstream. The water leaving the uplands not only supports aquatic ecosystems downstream but is the main drinking water source for many people living in the South West. Furthermore, functioning peatlands regulate water supply, slowing the flow of water from the uplands during rainfall and gradually releasing water during dry spells.

Ecosystem services provided by a functioning peatland.

Erosion at Hangingstone Hill, Dartmoor.

The peatlands of the South West of England lie at the most southerly and westerly limit of the bio-climatic envelope of peat-forming ecosystems[3] (i.e. areas with suitable temperature and precipitation conditions). Consequently, these bogs are vulnerable ecosystems that must be protected. They are also invaluable indicators of what may happen to other more northerly peatlands, in the UK and elsewhere, as the climate warms and rainfall patterns change.

Natural and anthropogenic pressures on the peatlands of the South West are typical of those occurring globally, they include drainage, peat extraction, over-grazing, burning, disturbance from military use, climate change and nutrient deposition. These pressures have altered the natural feedback cycles which maintain these ecosystems, leaving them increasingly vulnerable to erosion and ecological/hydrological degradation.

Rivers sourced on peatlands provide 70 % of all UK drinking water.

Peatland restoration started on Exmoor in 2006 as it became apparent that many of the peatlands we rely on for vital ecosystem services were in a degraded and worsening state. South West Water's Upstream Thinking Programme, working with a multitude of stakeholders, has restored a total of 24.8 km^2 (2480 ha) of peatland across Exmoor and Dartmoor since 2010. As part of their 25-year environment plan the Department for the Environment, Food and Rural Affairs recognises the need to restore and protect our peatlands[4], funding the South West Peatland Partnership project to restore 16.8 km^2 (1680 ha) of peatland across Bodmin Moor, Exmoor and Dartmoor by 2020.

Research has been central to the restoration programme; to better understand the current state of these peatlands, design appropriate restoration plans and evaluate the success of restoration. The following document outlines our findings since 2010 working within Dartmoor and Exmoor National Parks.

Restoration at Hangingstone Hill, Dartmoor has left pools of water where there were erosional pans.

Pools of water form behind peat dams, Lanacombe, Exmoor 2014.

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Exmoor: a Shallow Peatland

Since the last ice-age, humans have been using and altering the moorlands of Exmoor. Peat cutting by hand has been practised on Exmoor since medieval times, and features indicate that large amounts of peat have been removed for domestic use[1]. From the 1820s the Knight family constructed a dense network (approximately every 20 m) of hand dug ditches (about 0.5 m wide by 0.5 m deep) (Figure 1) to reclaim the high moors for arable production[2] resulting in 618 km of drainage ditches[3] (Figure 2). Additional larger ditches (>1.5 m wide) were machine dug between the 1960s and 1980s to drain specific areas such as springs[4]. The moorlands have also been subject to burning, in a further attempt to improve pasture for grazing. Collectively, these management practices led to a drying out of the peatlands and an increase in the dominance of purple moor grass (*Molinia caerulea*).

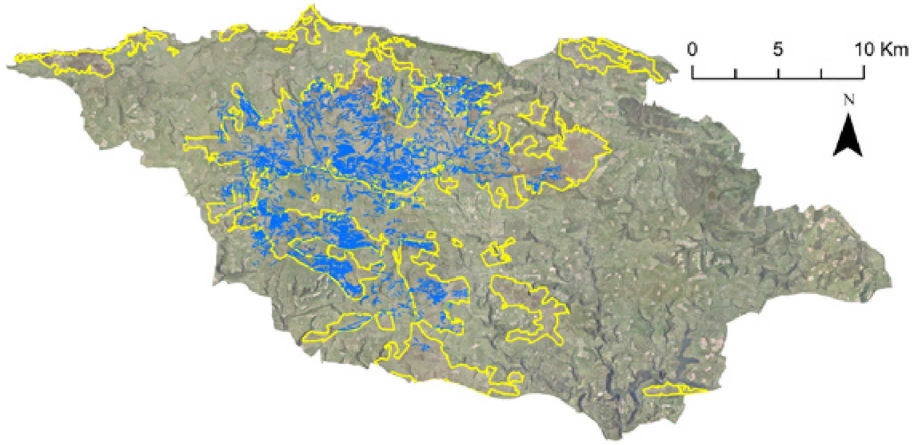

Figure 2 Exmoor National Park showing the fragmented moorland areas (yellow) and mapped drainage features (blue).

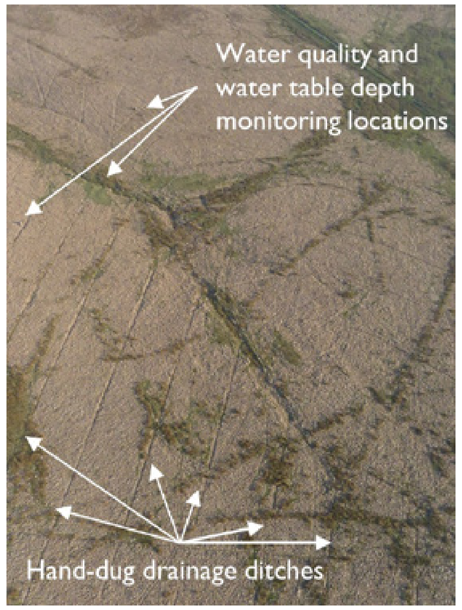

Figure 1 Photograph from an Unmanned Aerial Vehicle showing the closely spaced hand-dug drainage features typical of Exmoor and water quality and water table depth monitoring locations at Aclands.

Peat cutting on Brendon Common in the 1990s.
Image courtesy of Rob Wilson-North.

The cool (minimum of 2 °C in February, rising to 18 °C in July[5]) and wet (1353 mm per year) conditions on the uplands of Exmoor enable peat to form. However, peat across Exmoor is relatively thin, with 53 km^2 (5300 ha) of the 65 km^2 (6500 ha) of blanket bog less than 30 cm thick[6,7].

Monitoring the effects of restoration has focused on two small headwater catchments of the River Barle, within North Exmoor Site of Special Scientific Interest. They are located between 380 and 465 m above sea level. These catchments, Aclands (Figure 3) and Spooners (Figure 4), were chosen to be representative of the general peatland conditions found across Exmoor. Both catchments contain vegetation typical of mire and wet heath communities, such as *Sphagnum* spp. and cotton grasses (*Eriophorum* spp.) but are dominated by purple moor grass (*Molinia caerulea*). The catchments are currently in use as rough grazing.

Aclands and Spooners were restored, by ditch blocking with peat and wooden dams, in spring 2013 and 2014 respectively (Figure 5).

Additional monitoring occurred at Long Holcombe along a gradient between wet bog vegetation (*Sphagnum* spp. and cotton grasses (*Eriophorum* spp.)) with peat depths in excess of 0.5 m, to dry purple moor grass (*Molinia caerulea)* dominated grassland with peat depths of less than 0.2 m.

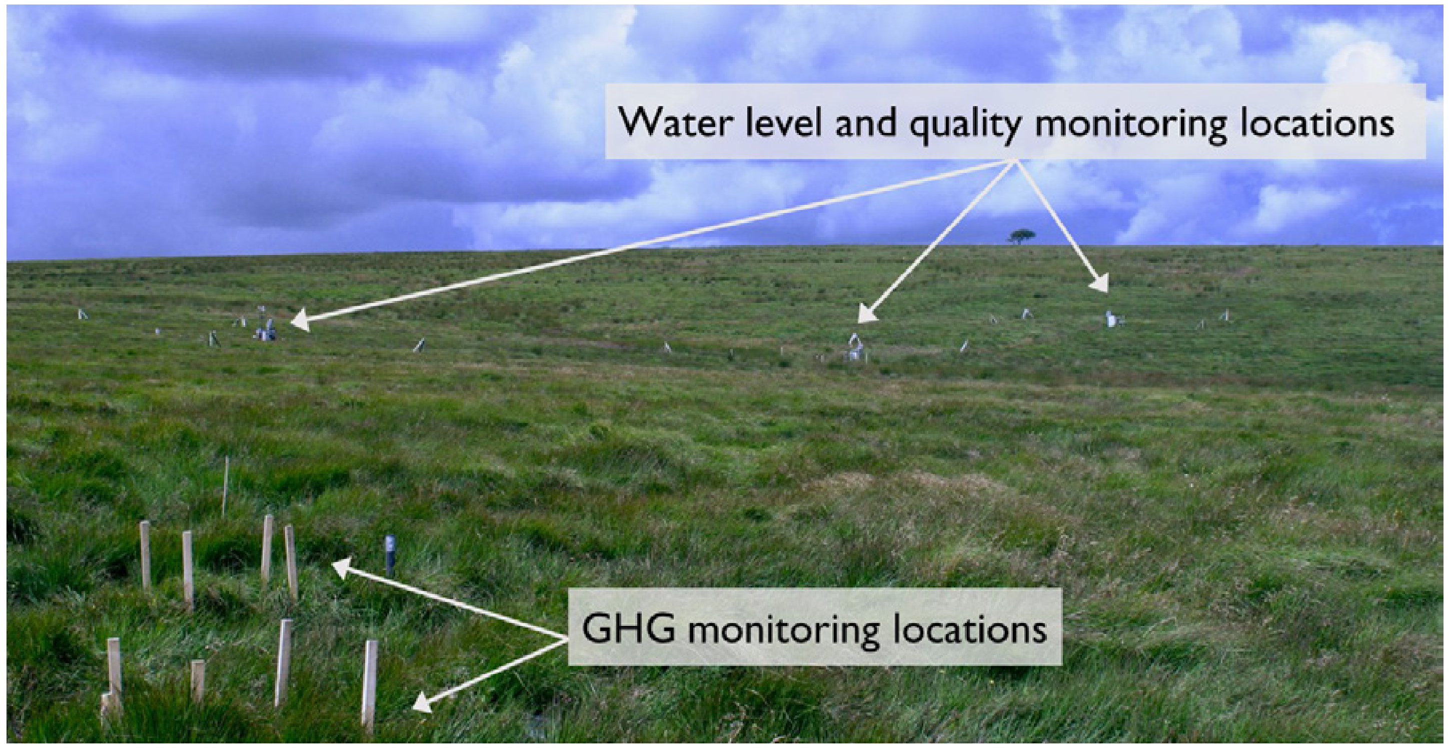

Figure 3 Summer in the Aclands catchment with a greenhouse gas monitoring (GHG) location in the foreground and water level and water quality monitoring across small (left), large (middle) and medium (right) ditches in the background.

Figure 5 Post-restoration, peat dams create pools of water at Spooners.

Figure 4 Unmanned Aerial Vehicle borne imagery of the dry purple moor grass (*Molinia caerulea*) dominated Spooners catchment, post-restoration.

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Figure 6 **Extent of peatland degradation across Dartmoor.**

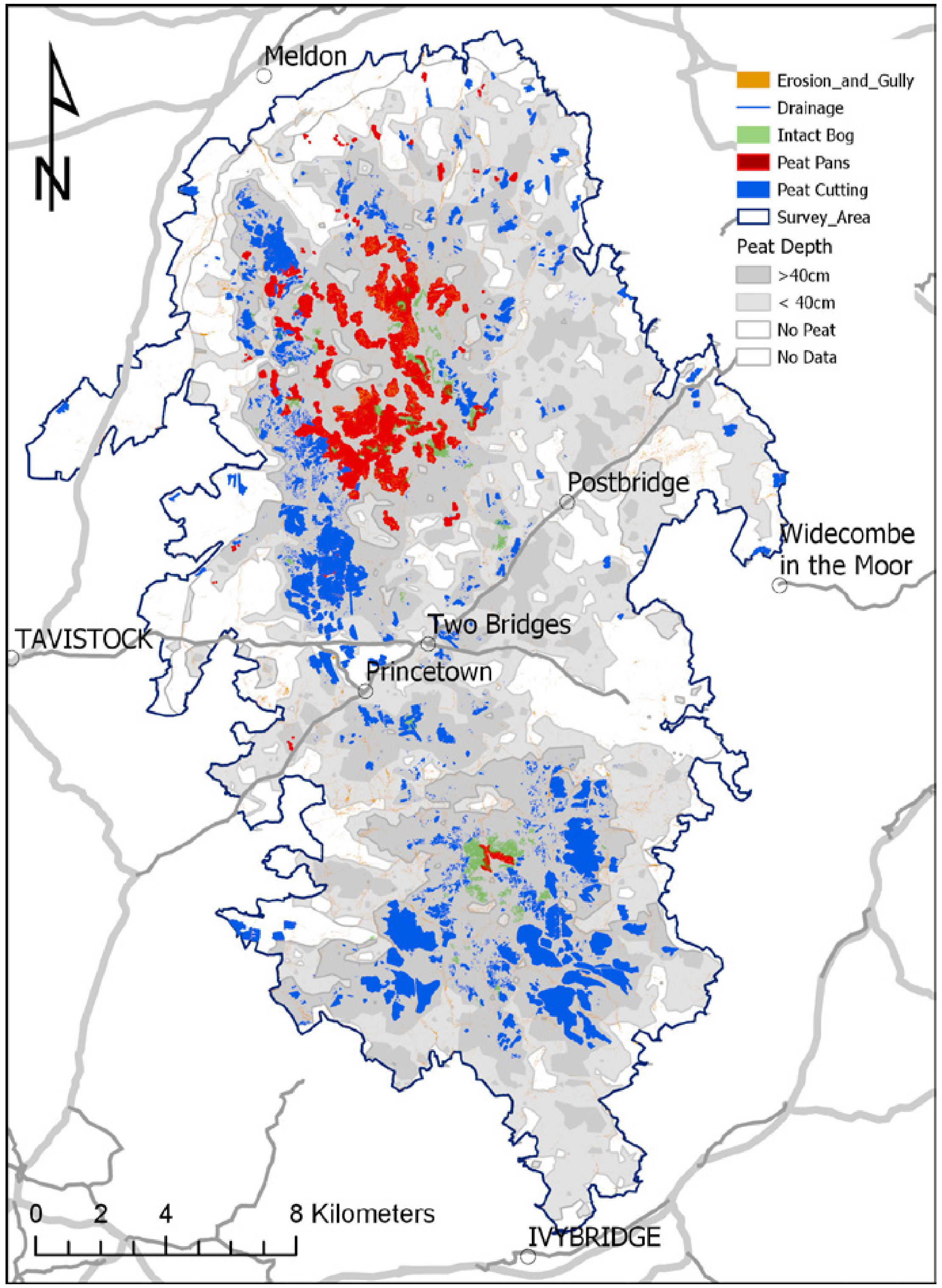

Figure 9 **White cotton grass (*Eriophorum* spp.) flowers bloom in the restored area.**

Dartmoor: a Deep Peatland

The uplands of Dartmoor have also been shaped by human hand since the last ice-age. The uses have been varied and included domestic and commercial peat cutting, tin and china clay extraction, granite quarrying, drainage for agricultural improvement, grazing with and without burning to improve pasture, forestry, military activity and more recently recreation. These uses have each left their mark on the landscape so that today 29 km^2 (2900 ha) of the peat on Dartmoor is significantly and directly ecohydrologically degraded or damaged (Figure 6) by erosional gullies, peat cuttings, drainage ditches and bare peat[1].

A pilot study into the effectiveness of restoration was established in 2013 in an area of degraded blanket bog on the north moor: Flat Tor Pan. The site was chosen as typical of the extensive areas of blanket bog with a pattern of erosional peat pans (generally <1 m deep) between vegetated peat haggs. Where the gradient is steeper these peat pans form dendritic erosional features (Figure 7).

Climatically, the uplands of Dartmoor are cool (minimum of 2 °C in February rising to 18 °C in July) and wet (2230 mm annually[2]). Flat Tor Pan lies at 515 m above sea level and has peat between 3.6 and 4.0 m thick[3], which is above the average for Dartmoor (0.81 m)[4]. Where vegetated, Flat Tor Pan has vegetation typical of blanket mire (including *Sphagnum* spp. hare's-tail cotton grass (*Eriophorum vaginatum*), purple moor grass (*Molinia caerulea*) and deer grass (*Scirpus cespitosus*). Between these vegetated haggs there are eroding pans of exposed peat sometimes with sparse bog cotton grass (*Eriophorum angustifolium*). The land lies within the North Dartmoor SSSI, the Dartmoor Special Area of Conservation (SAC) and the Forest of Dartmoor and is used for common grazing.

Restoration occurred in August and September 2014, and involved moving peat, either from borrow pits or small protuberances, to block gullies and disconnect dendritic erosional features (Figures 8 and 9).

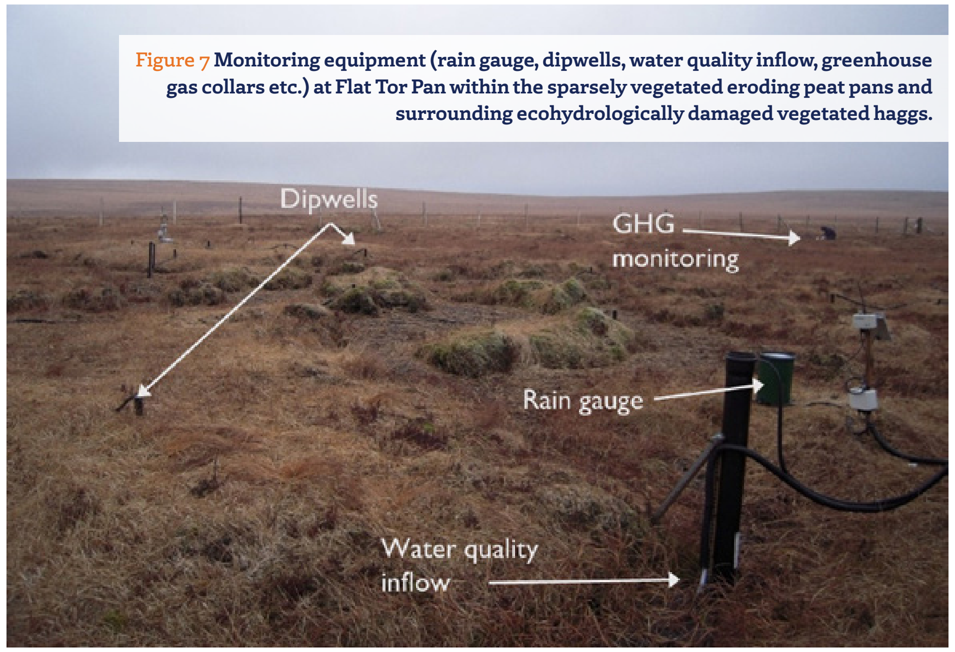
Figure 7 **Monitoring equipment (rain gauge, dipwells, water quality inflow, greenhouse gas collars etc.) at Flat Tor Pan within the sparsely vegetated eroding peat pans and surrounding ecohydrologically damaged vegetated haggs.**


Figure 8 **Peat blocks disconnected the erosional features forming isolated pools.**

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BODMIN MOOR, EXMOOR AND DARTMOOR

RESTORATION

Wooden block construction at The Chains, Exmoor.

Restoration planning, methods and outcomes

Peatland restoration represents an opportunity to make a significant difference to the degrading peatlands of the South West of England. The South West Peatland Partnership is the umbrella name that brings together the local delivery of peatland restoration across the three moors of Bodmin Moor, Dartmoor and Exmoor. Its aim is to work together with a wide range of partners (see back cover) to restore these peatlands and bring about sustainable hydrological management in upland river catchments. The Exmoor Mires Partnership is the culmination of several projects that have run from 1998-to date, whilst the Dartmoor Mires Partnership has had two phases of restoration; a pilot project (2010-2015) and the current phase (2018-2021). The Bodmin Moor Peatland Partnership has been running since 2018.

Restoration work

The overall aim of restoration is to raise water tables, decrease peak flows from storms and increase base flows in dry periods. Blocks (dams) are used to disconnect dendritic erosional features and are placed along ditches and erosional gullies, thereby diverting water out of the ditch and across the land surface or through the peat soil.

The restoration methods used are based on national guidance techniques[1] which have then been adapted to reflect the local requirements and techniques[2] needed. These techniques have evolved over the years through trial and error, and through advice and requests from landowners and farmers.

The decision for the type of block used in an area depends on several factors, such as: the size of the ditch or erosional feature, the gradient of the slope, the volume of water that flows down the ditch and the landscape impact[2]. Blocks installed in the ditches can comprise a combination of peat, wood, stone, bales (made out of purple moor grass (*Molinia caerulea*)) or grey willow (*Sambucus nigra*). The wood for the blocks comes from local plantations, which is then planked to our requirements and left untreated.

Before any restoration takes place, the mires staff carry out a variety of in-depth planning, assessment, research and consultation in order to compile a Restoration Plan for each site representing a best practice approach to peatland restoration. Each plan assesses the positive and negative impacts of the restoration on the ecology, historic environment, landscape, access arrangements, land management practices, and estimates the costs associated of carrying out the restoration works. All appropriate government bodies, landowners, commoners, graziers, tenants and farmers have input into the plans and therefore the restoration that happens on the ground.

Restoration is carried out between August and April, to avoid the ground nesting bird breeding season, using local contractors to deliver the bulk of the work and a pool of volunteers who tackle minor maintenance works. Owing to the delicate nature of peat and to reduce the physical and visual impact on the landscape, specific diggers are used. They have wide tracks to provide greater weight distribution (resulting in ground pressures less than a human footprint), a rotating bucket head in order to reduce the amount the digger moves around, and a toothless bucket to ensure less disturbance, particularly to any historical artefacts hidden in the peat.

Reprofiling steep erosional slopes at Flat Tor Pan, Dartmoor, December 2019.

Restoration in progress within the Spooners monitoring catchment, Spooners, Exmoor.

Willow faggot dam in a steep gully, Hoar Moor, Exmoor, February 2019. Willow was used in this situation to slow flows, trap sediments and create small areas of wet willow woodland. It was part of wider works to reinstate the River Quarme back into its original course, having been diverted in the early twentieth century.

Peat blocks along a drainage ditch showing water stored behind the blocks, Great Buscombe, Exmoor.

To date (January 2020), on Exmoor over 26.03 km^2 (2603 ha) of damaged peatland has had initial ditch blocking works carried out – a total of 25,607 blocks installed in 250 km of drainage ditches. A further 7.5 km^2 (760 ha) is considered unsuitable for restoration. On Dartmoor 1.8 km^2 (180 ha) of degraded blanket bog, characterised by dendric erosional features and bare peat soil, has been restored and rewetted.

Total capital cost of the restoration across the three moors to date (January 2020) is about £4 million. Costs per hectares range from £306/ha^2 to around £5000/ha. This huge variation is dependent on a variety of factors such as the need for unexploded ordinance surveys, how remote a site is, and the range of differing practical interventions required.

The economic benefits of peatland restoration are wide-ranging, both directly from the process of restoration, e.g. sourcing materials locally and employing local contractors to carry out both restoration and monitoring works, and indirectly through the effects of restoration e.g. payments for ecosystem services provided by the peatland generating income to farmers via Higher Level Stewardship schemes for moorland maintenance, restoration and re-wetting.

Survey and monitoring

Biodiversity

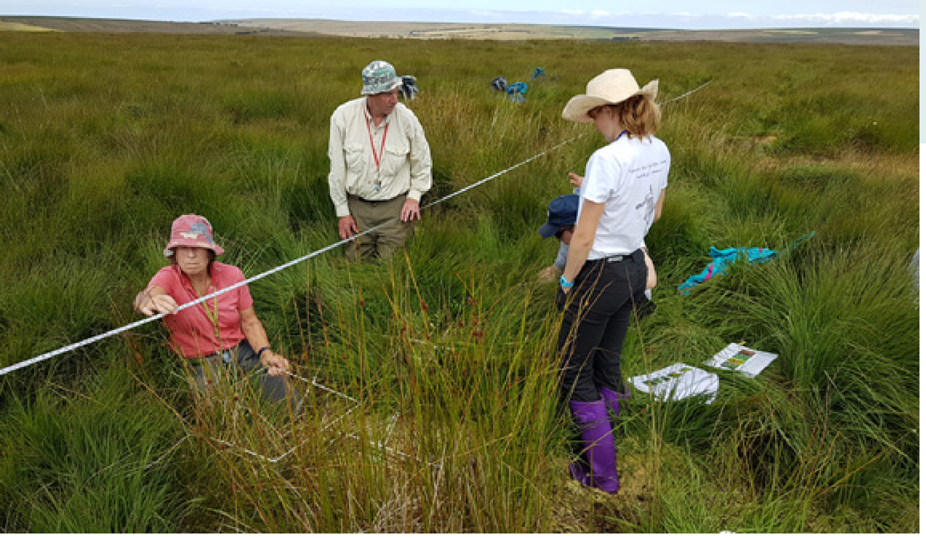
Biodiversity monitoring aims to detect changes (hopefully positive) in the species and habitats associated with healthy, hydrologically functioning peatlands.

The vegetation present is strongly linked to other ecosystem services, such as the production of dissolved organic carbon and the drawdown of gaseous carbon, which are much harder/more costly to monitor. Therefore, if we see bog species like *Sphagnum* mosses and cotton grasses (*Eriophorum* spp.) returning and species like purple moor grass (*Molinia caerulea*) declining, we can infer that there have been changes in the hydrology and ecological functioning of the peatland.

Vegetation monitoring on Exmoor (28 sites) shows an expansion in the distribution of *Sphagnum* 3 years post-restoration. This increase is significant ($p<0.005$) for sites 7 or more years post-restoration. A similar analysis of purple moor grass (*Molinia caerulea*) cover (31 sites) showed no sign of reduction until at least 11 years after restoration[3].

On Dartmoor a significant increase in mire species such as bog cotton-grass (*Eriophorum angustifolium*), *Sphagnum denticulatum, Sphanum cuspidatum* and *Sphagnum papillosum* within 3 years following restoration has been observed. However, a return to favourable blanket bog vegetation is expected to take 10 or more years[4].

Breeding bird assemblages, particularly those species associated with wet peatland habitats, give us an insight into the success of peatland restoration. On Exmoor, breeding snipe (*Gallinago gallinago*) have



Vegetation monitoring along a transect, Squallacombe, Exmoor.

A Mesolithic (7000 to 4000 BCE) hammer stone found at Horsen Farm, Exmoor during mire restoration field work.

Type	Exmoor	Dartmoor
Site surveys (combined walkover and desk-based assessment)	18	7
Palaeoenvironmental Assessments	8	3
Watching Briefs	2	5
Landscape Studies	2	
Geophysical Surveys	7	
Measured, earthwork Surveys	9	
Excavations	7	
Research Reports	5	2
Additional HER entry reports	10	6

Number and type of historic environment assessments carried out as part of peatland restoration

been observed at two restoration sites which previously had none[5,6]. In the context of there being only eight breeding snipe locations on Exmoor in 2011, this is a notable result. Whilst on Dartmoor, snipe (*Gallinago gallinago*) have increased considerably and dunlin (*Calidris alpine*) increased, particularly in the areas that have been restored e.g. Winney's Down and Cowsic Head[7].

The Exehead/ Blackpitts (Exmoor) restored sites have become the best sites in Somerset for black darter (*Sympetrum danae*) and common hawker (*Aeshna juncea*) dragonflies, both upland species which require open water. This success is due to the pools created by the restoration in 2007 – prior to this there was no surface water on the site[8].

Historic Environment

Exmoor and Dartmoor contain a wide range of historic sites and features that often survive well thanks to the less intensive agriculture and development compared to lowland areas. The peat itself often covers archaeological sites and deposits, preserving organic materials and environmental evidence that does not survive in drier conditions. To further inform and mitigate the impact of mire restoration on the historic environment we combine information from walkover surveys and desk-based assessments of existing knowledge into site plans. Where thought necessary, additional work is carried out to ensure the historic environment is both well-recorded and understood. Such work includes palaeoenvironmental studies, geophysical and earthwork surveys, excavations and watching briefs. Many previously unrecorded archaeological features and sites have consequently been identified as a consequence of peatland restoration (over 300 on Exmoor), ranging in date from around 6000BC to the 20th century. The new evidence has included prehistoric standing stones and cairns, nineteenth-century mining works, networks of medieval trackways and Second World War military training features. This data has allowed the existing Historic Environment Records (HER) to be expanded and enhanced.

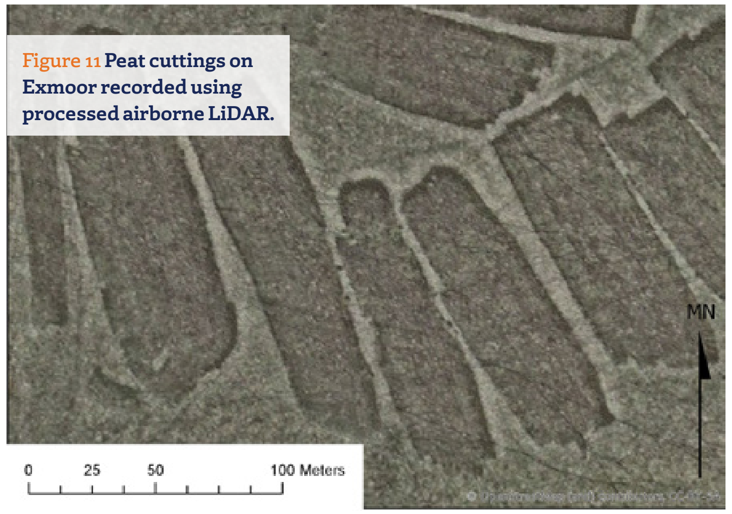


Figure 11 Peat cuttings on Exmoor recorded using processed airborne LiDAR.

In some cases, we have carried out additional case studies that go beyond individual sites and represent new research into aspects of the historic environment that may be impacted by mire restoration. This includes investigations into domestic and industrial peat cutting on both moors, the form and dating of deserted field systems on Codsend Moor (Exmoor) and the soils of Exmoor before the formation of peat. One such study identified tephra – volcanic dust deposits that can precisely date peat deposits and the evidence of environmental change held within them – for the first time in the South West[9].


Pre-restoration 2006.
Post-restoration 2006.
Post-restoration 2019.

Figure 10 Fixed point photography from Roostichen, Exmoor; pre-restoration (2006), immediately post-restoration (2006) and 13 years post-restoration (2019).

Landscape

Peatland restoration aims to bring about landscape change. In order to demonstrate and monitor landscape change associated with restoration fixed point photography is used (Figure 10). There are now over 60 pre- and post-restoration locations across Exmoor and Dartmoor.

Comparing aerial imagery dating from the 1940s to present day images enables us to map and analyse how that landscape was, is, and has changed through time. At the same time, this captures modern day archaeology in the form of our restoration work. Airborne LiDAR (Light Detection and Ranging) and Unmanned Aerial Vehicle (UAV) photogrammetric surveys record our landscapes in another dimension at up to centimetre accuracy. These surveys clarify features such as individual peat cuttings (Figure 11) which are often hard to distinguish by human eye on the ground.

Communication and Education

Communicating all the work and research undertaken is a vital element of the partnership, as is learning from those who manage and work on the peatlands. Involving local individuals, community groups, the farmers who manage the land and partner organisations has enabled successful landscape peatland conservation to happen on the ground. A programme of education, events and publications have been delivered in order that the numerous people who work in and visit these landscapes can gain a greater understanding and experience of peatlands. For example, the '*Bogtastic*' CLOWNS Play Bus and the '*Bogtastic*' Summer Festival, has engaged with over 4000 people.

Enjoying the 'Bogstacle Course' at Bogtastic.

Volunteers are actively involved in a wide range of activities within the project including running, leading and organising educational walks, talks and events; practical work such as small-scale ditch blocking; survey and research; publicity work and office work. Over 1000 days of volunteering have been carried out on the project.

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How does the restoration of a shallow peatland affect water tables, runoff and water storage?

- Restoration can significantly alter rainfall runoff regimes in restored catchments.
- Peak runoff from comparable rainfall events can be reduced by as much as 21 %.
- Total runoff generated from comparable rainfall events can be reduced by as much as 32 %, as water leaves the restored catchment more slowly, increasing catchment baseflow between rainfall events.
- Rainfall runoff response is catchment specific, smaller rainfall events can result in a limited increase in storm runoff.
- In the short term (<5 years post-restoration) average water tables remain at similar levels post-restoration.
- Water table responses to restoration are spatially complex and in locations where drainage had most significantly altered ground water storage, water tables are seen to rise by as much as 4 cm.

In an intact state, peatland landscapes form as wetlands with water at or near the ground surface for most of the year. These areas are home to specialist plant species adapted to grow in waterlogged ecosystems. The storage and release of water from such landscapes is inherently linked to the way the ecosystem functions as a store of carbon and regulator of river flow. Peatland restoration aims to re-establish more natural hydrological processes in historically drained and damaged peatlands. Across two restored headwater catchments (Aclands and Spooners) discharge was estimated in the main channel leaving the catchment. Additionally, water tables were monitored within and surrounding several drainage features using a network of dipwells extending to the bottom of the peat soil (Figure 12). Water tables are measured as depth to water down from the ground surface.

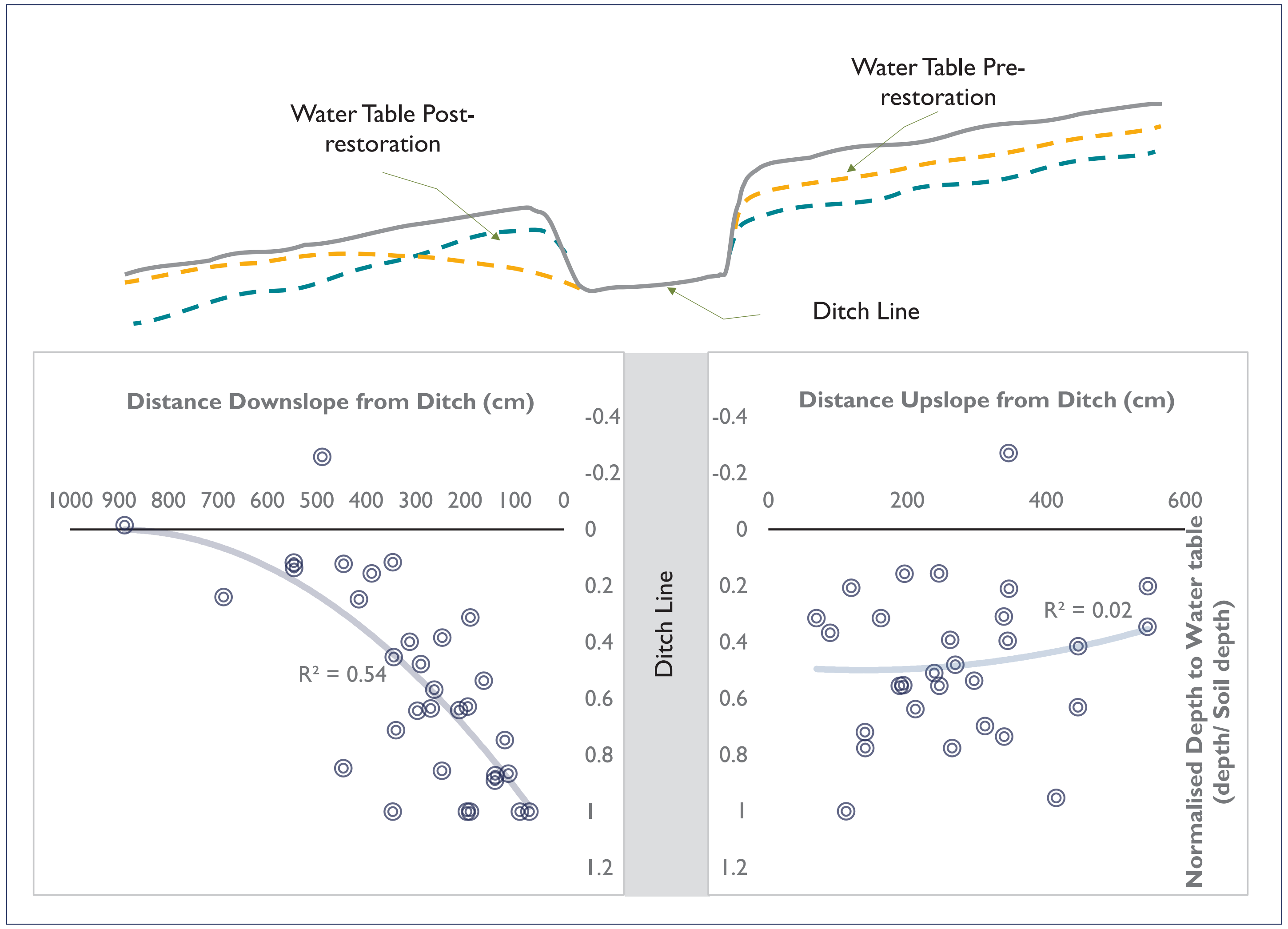

Figure 13 **Above: conceptual diagram of water table response to restoration within Spooners catchment. Below: Average water table depth plotted for all monitored dipwells surrounding ditches in the Spooners catchment pre-restoration.**

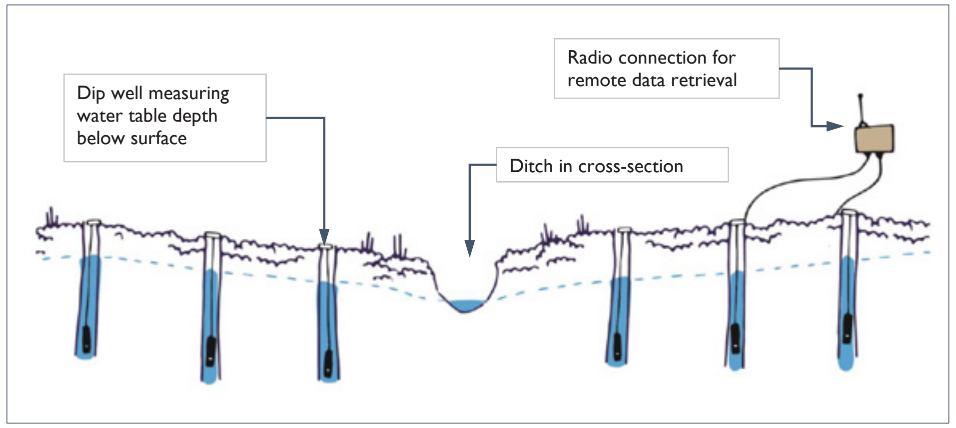

Figure 12 **Illustration of a dipwell array surrounding a restored drainage ditch in Spooners catchment.**

Water Table Depth

The response of water table depth to restoration is spatially and temporally complex, particularly as drainage features often cut across-slope (Figure 13). Pre-restoration, water tables are seen to be lower on the downslope side of drainage features, decreasing with proximity to drains (Figure 13 and 14). Upslope of cross-slope drainage, water tables do not vary with distance to the drain and are persistently below the soil surface[1].

Post-restoration, changes are observed in water table depths, but these are confounded by significantly reduced rainfall in the years monitored post-restoration, compared to those pre-restoration (Figure 15). Despite this, immediately downslope of drainage features, water tables are seen to increase by an average of 4 cm and become more variable (Table 1, Figure 14) following ditch blocking. However, immediately upslope of drainage features, water tables are seen to be lower (average of ca. 9 cm) illustrating the spatial complexity of the restoration effect. These results suggest restoration has equalised

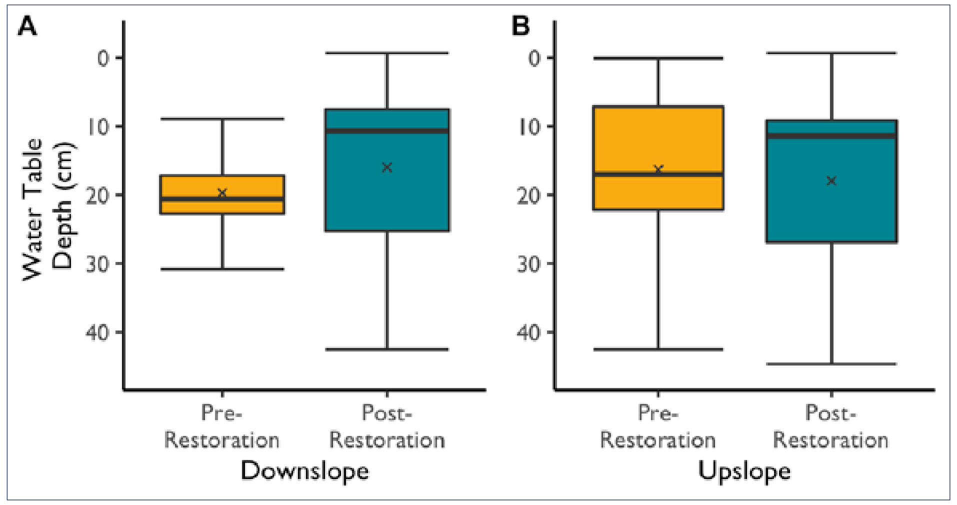

Figure 14 **Box and whisker plot of water table depth within 1 m of a drainage ditch, relative to hillslope position, pre- and post- restoration at Spooners. Water tables downslope of drainage ditches are seen to rise by as much as 4 cm.**

Table 1: **Water table depth from soil surface (WTD) statistics for locations within 1 m of a drainage feature within Spooners catchment.**

	Pre-restoration Downslope	Post-restoration Downslope	Pre-restoration Upslope	Post-restoration Upslope
Mean WTD (cm)	19.7	16.0	12.8	20.0
Median WTD (cm)	20.6	11.0	7.2	12.0
Standard Deviation	4.7	12.0	10.9	13.3
Range (cm)	42.4	43.2	40.5	41.4
Minimum (cm)	0.1	-0.7	0.3	3.3
Maximum (cm)	42.5	42.5	40.7	44.7
Number of measurements	71333	176336	69149	175027

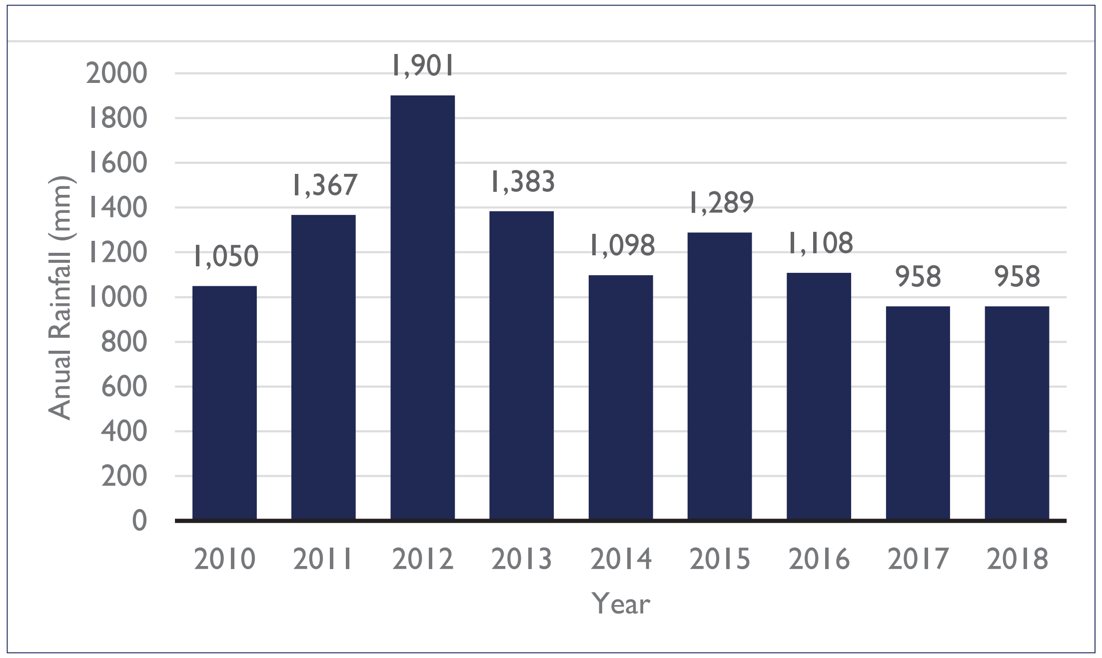

Figure 15 Annual rainfall totals for Spooners catchment from 2010 to 2018; restoration occurred in 2013. The atypical pre-restoration rainfall of 2012 is notable at nearly double that of 2017.


Restoration in progress at Spooners.

water table drawdown in the areas immediately adjacent to drains, and whilst water tables remain predominantly below the surface, drainage features may export less water from the soil.

Spooners Catchment Runoff

Runoff production within the larger Spooners catchment was significantly altered by restoration. Rainfall/runoff events with comparable contributing rainfall, had significantly less total discharge (Figure 16 and 17) and a lower peak event discharge post-restoration ($p<0.001$).

For smaller rainfall events (<10 mm), total event discharge and peak event discharge were reduced by 32 % and 29 % respectively ($p\leq0.001$) post-restoration. For larger rainfall runoff events, this effect is less statistically significant ($p=0.002$ and $p=0.036$, for total discharge and peak event discharge respectively), indicating that the reduction in peak and total event discharge is more pronounced for smaller events. Overall, total discharge reduced by an average of 32 % and peak event discharge reduced by an average of 21 %. These results demonstrate that restoration has provided significant short-term buffering of rainfall runoff at Spooners, particularly for small rainfall events that do not overwhelm the temporary surface storage created behind peat dams.

Aclands Catchment Runoff

The restoration response within the smaller catchment (Aclands) was less pronounced. For larger rainfall events (>10 mm), total event quickflow and peak event discharge were not significantly different ($p>0.05$). Contrastingly, for smaller rainfall events (<10 mm), total and peak discharge were significantly higher post-restoration (mean >100 % at $p<0.05$). This indicates catchment rewetting may have caused a small increase in runoff connectivity for smaller rainfall events, post-restoration. However, for larger rainfall events, that are more important for flooding and water treatment, this change does not lead to significantly increased peak or total runoff.

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Monitoring equipment in pools formed behind blocks following restoration.

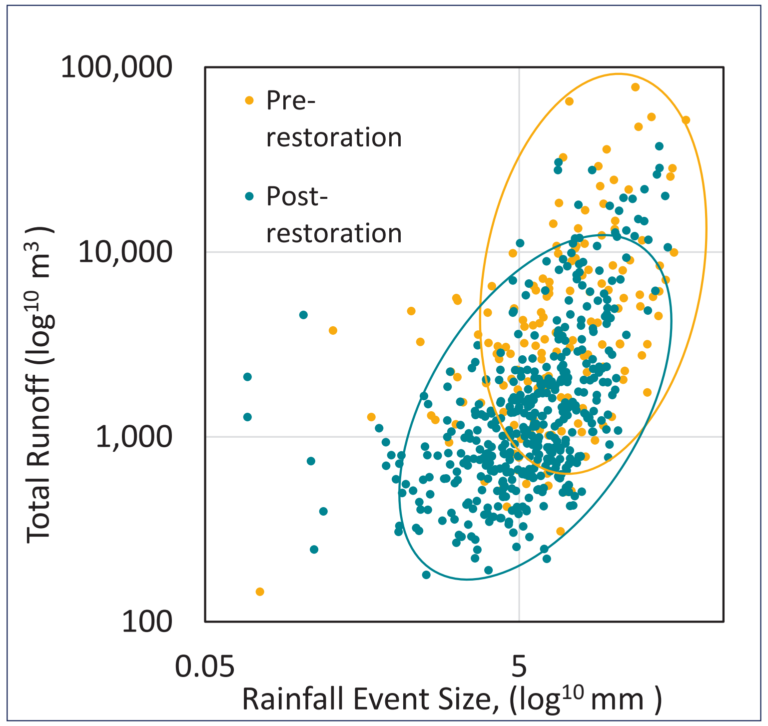

Figure 16 Total runoff (quickflow) vs total contributing rainfall for individual response events at Spooners catchment, pre- and post-restoration. Coloured ellipses illustrate the broad change in response distributions post-restoration.

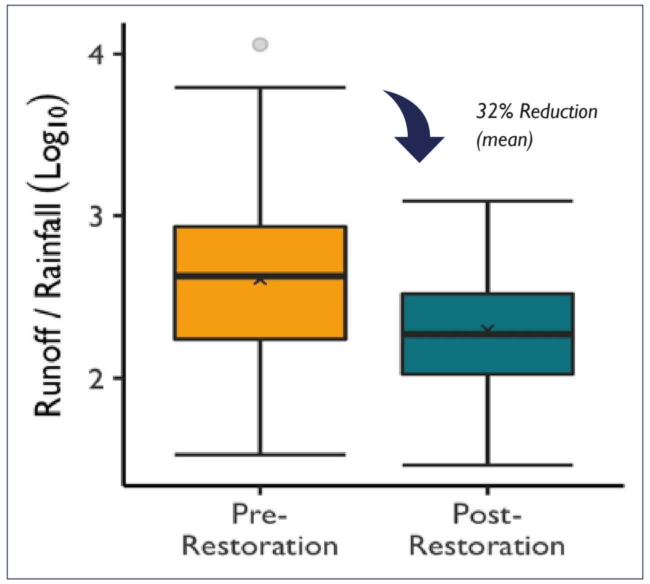

Figure 17 Box and whisker plot of the ratio of rainfall to runoff response ($\log_{10}$ transformed) at Spooners catchment pre- and post-restoration. Runoff is reduced by 32 % (mean) post-restoration.

How does the restoration of a deep peatland affect storm runoff and water storage?

- Average (spatially and temporally) water table depths have increased post-restoration, they are now 2.45 cm nearer to the surface.
- Pre-restoration, maximum water table drawdown (i.e. depth during dry weather) was between 22 and 48 cm below the surface. Post-restoration this reduced to between 17 and 37 cm, indicating an average additional 7.3 cm of permanent deep water storage in the peat soil.
- Restoration removed permanently dry areas next to peat pans, which now exhibit water levels >10 cm above the surface during periods of high rainfall.
- Diffuse overland flow and deep subsurface flow outside of the main gully, dominate total runoff post-restoration. Runoff through the monitored gully reduced by approximately 66 % post-restoration.
- The average in-gully pooled water storage increased by 32 cm post-restoration. Minimum pooled water within the gully also increased by around 4 cm post-restoration.

Peatlands form as wetland landscapes with water at or near the ground surface and plant species adapted to grow in such an environment. The way peatland landscapes store and release water is inherently linked to the way they function as stores of carbon and regulators of river flows. Peatland restoration aims to re-establish more natural hydrological processes in drained or damaged areas, leading to more secure carbon storage (or accumulation) and reduced variation in downstream river flows. The monitoring design at Flat Tor Pan measured spatial patterns of water table depth and runoff from a single gully and its associated drainage area. Water tables, measured as the depth of water below the ground surface, were monitored within and surrounding dendritic drainage features, using a network of dipwells extending 2 metres below the peat surface

Water Storage

Pre-restoration, gully runoff was characterised by flashy flows, an ephemerally dry gully and dendritic erosional "pan" features (Figure 18). Average water table depths pre-restoration were ca. 20 cm below the surface in vegetated areas, but fell to >40 cm below the soil surface during dry periods. The pan features rarely supported water tables above the surface; only during the wettest conditions (Figure 19). In the vegetated areas closest to the bare peat pans (0 to 1 m from the edge), water tables never rose to within ca. 5 cm of the surface (Figure 19) which would be considered normal in a healthy peat bog. Consequently, the areas of vegetated peat immediately surrounding the bare peat pans were permanently dry, causing peat collapse and the expansion of the dendritic pan/gully

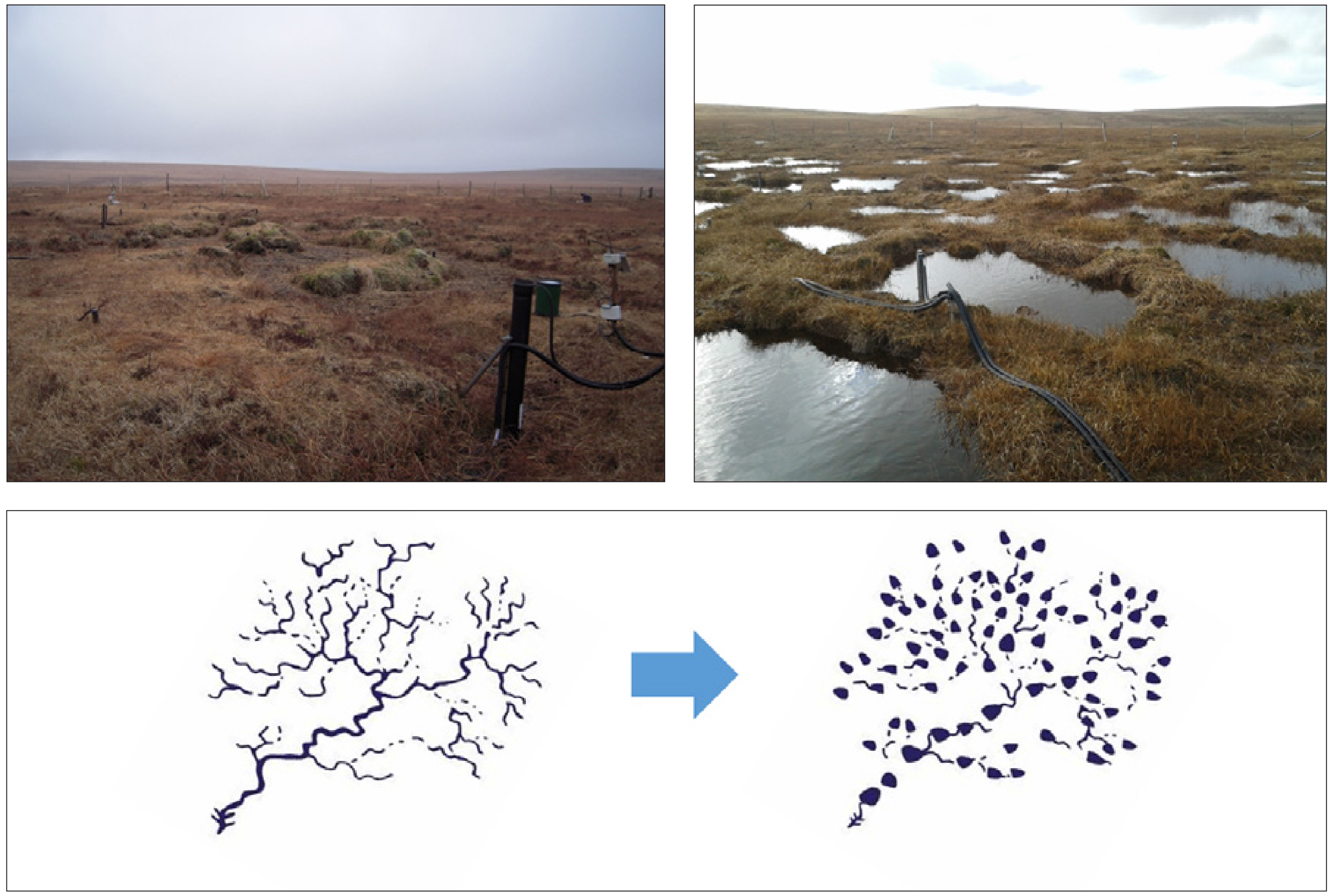

Figure 18 **Photos and ilistration of how restoration has altered the hydrological connectivity of the monitored dendritic landforms from pre-restoration (left) to immediately post-restoration (right).**

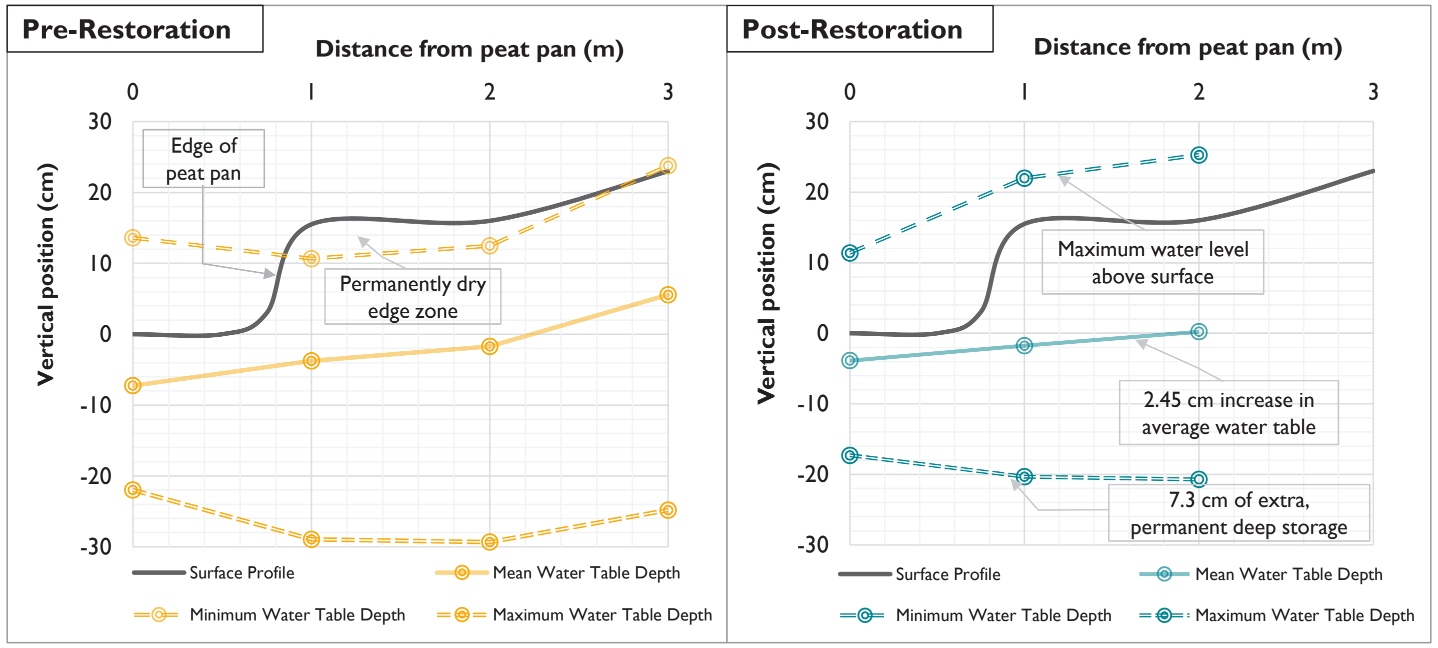

Figure 19 **Minimum, mean and maximum depth to water table (cm), pre- and post-restoration, relative to the average soil surface level for each of the distance classes measured. The black line ilistrates the spatialy averaged soil surface height for each of the measured distance classes.**

Sphagnum growth over monitoring equipment.

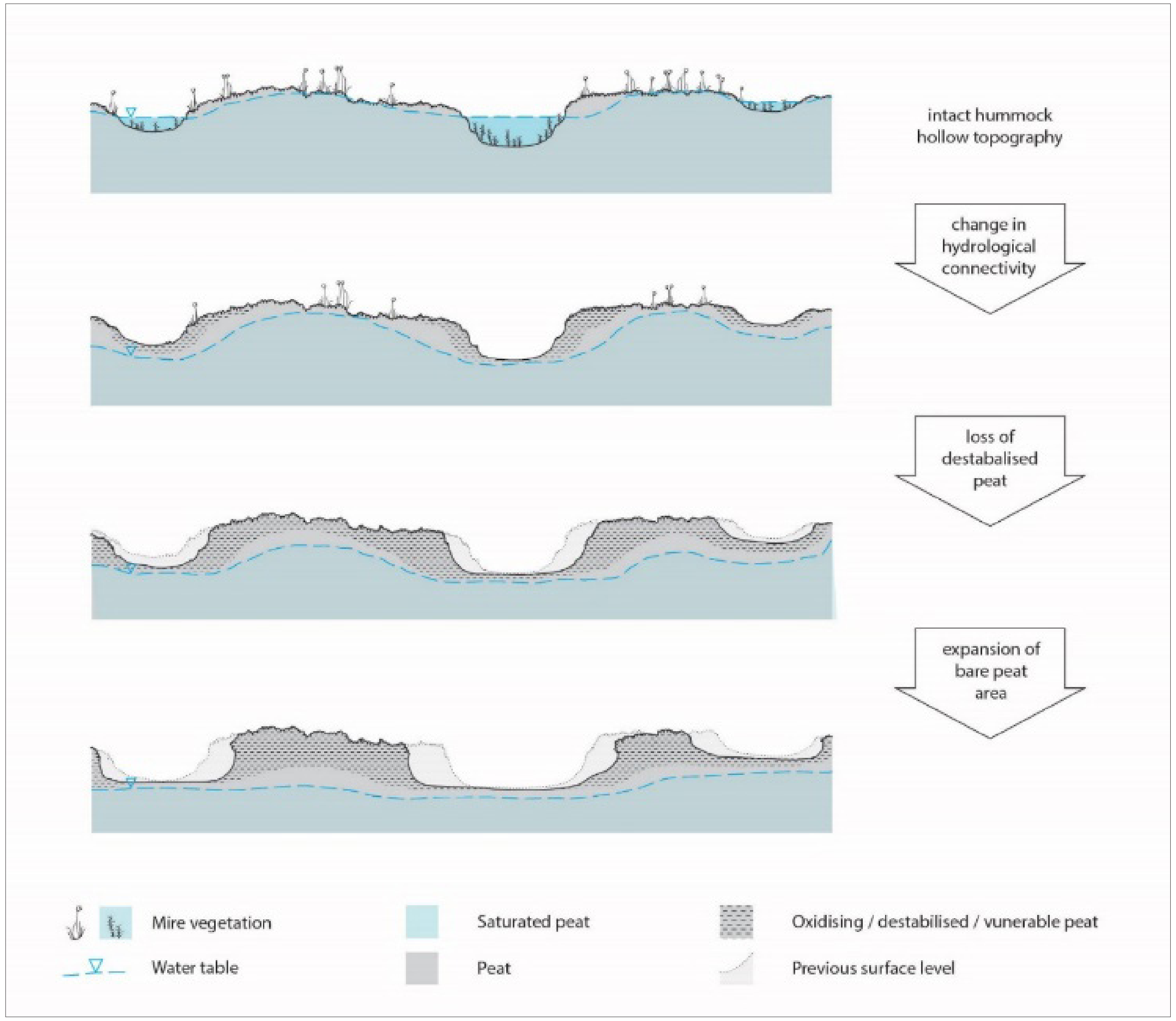

Figure 20 **Conceptual diagram of mechanisims driving dendritic landform expansion across Flat Tor Pan.**

areas (Figure 20). This suggests that areas of bare peat/vegetated haggs are active systems that may continue to expand without intervention via peatland restoration.

Restoration has had a profound effect across the monitored locations. Hydrological connectivity has largely been removed by drain blocking, resulting in previously sparsely vegetated and ephemerally dry pan areas exhibiting an average of 10.8 cm of additional standing water depth. Similarly, mean water tables have risen by 2.45 cm and maximum water table drawdown has reduced, providing an average of 7.3 cm of permanent, deep water storage in the peat soil.

The areas of permanently dry soil immediately adjacent to the peat pans now exhibit water tables well above the surface during periods of high rainfall (Figure 19), potentially reducing the oxidation and expansion of these regions and providing more suitable habitat for *Sphagnum* colonisation. These changes represent a step change in the hydrological function of the monitored area post-restoration which, in the longer term, would be expected to benefit peat forming plant species and ecology.

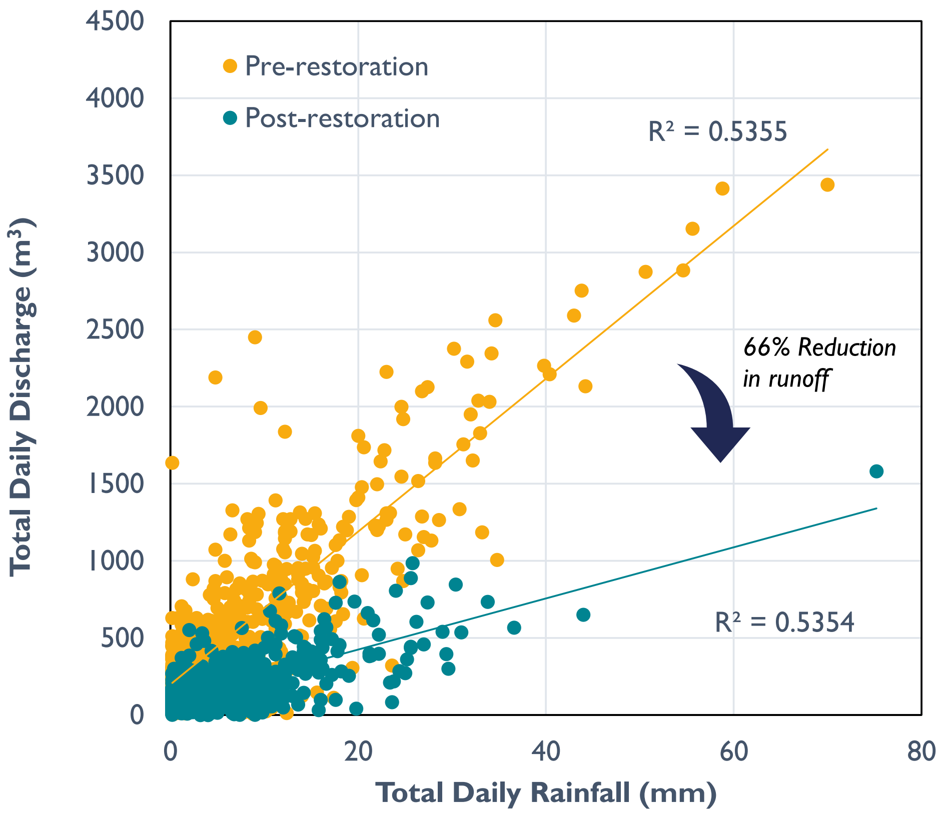

Figure 21 **Total daily rainfall vs total daily discarge leaving the monitored drainage/gully area on Flat Tot Pan. Post-restoration, the reduction in total daily runoff for a similar given rainfall is aproximatly 66 %, as illustrated by the arrow.**

Runoff

Post-restoration, runoff production through the gully was significantly reduced by ca. 66 % (Figure 21) and in channel storage (i.e. pooled water within the gully) increased by an average of 32 cm. However, it is important to note that these changes reflect both increased temporary storage in the peat soil/surface pools, and a switch to diffuse surface flow dominating storm runoff, post-restoration. This does not mean that less water is leaving the moorland, just that it now leaves via multiple pathways and much more slowly. Diffuse surface flow leaving the site outside of the gully is not measured here, but this type of flow is slower than channel flow and will, therefore, contribute to flood risk reduction and reduced peatland erosion.

The appendices are available to view at **www.exeter.ac.uk/creww/research/casestudies/miresproject**

Understanding water quality in runoff from degraded, shallow peatlands on Exmoor and the short-term impacts of restoration

- Pre-restoration, low water tables were linked to elevated dissolved organic carbon concentrations.
- Restoration has not had a statistically significant impact on any of the water quality parameters studied.
- Average DOC concentrations during runoff events pre-restoration range from 4.8 to 14.3 mg L^{-1} and post-restoration (3.5 to 13 mg L^{-1}).
- Water discolouration has not changed significantly post-restoration, and remains above EC standards (Abs^{400} of 1.5 Au m^{-1}).
- Greater improvements to the ecohydrological function, particularly vegetation change are needed before significant changes in water quality can be detected following restoration, such as the reduction in carbon loads which is only just becoming evident in the Spooners catchment.

Water held back by a peat dam post-restoration on one of the monitored ditches at Spooners.

The quality of the water running off Exmoor's peatlands impacts on aquatic life and drinking water management downstream. Due to the carbon-rich nature of peaty soils, the degradation of peatland function has been linked to elevated dissolved organic carbon (DOC) concentrations in the water leaving peatland catchments in recent decades. DOC enrichment in water leaving upland catchments represents an important pathway of carbon loss. DOC also discolours water and therefore has implications for water treatment as removing DOC from water is complicated, costly and can result in carcinogenic by-products.

Prior to this study little was known about the processes controlling the quality of water leaving Exmoor's peatlands and assumptions about the effects of peatland restoration on water quality were largely based on results from the deeper peatlands of northern England. Rainfall event based monitoring of water quality at Aclands and Spooners pre-restoration demonstrated that increased DOC concentrations occurred following warmer periods with deeper water tables, likely to be due to the aeration of the peat and stimulation of microbial decomposition[2]. This suggests that encouraging water table depths to levels more typical of peatland environments (at or near the surface) could reduce DOC concentrations.

Pre-restoration, DOC concentrations leaving the catchments (4.8 to 14.3 mg L^{-1}) were lower than the national average (31 mg L^{-1})[1], but were frequently in excess of the target of 5 mg L^{-1} (Figure 22A). Up to 4.5 years post-restoration there has not been a statistically significant change in DOC concentrations (3.5 to 13 mg L^{-1}) leaving either catchment (Figure 22A), though mean concentrations have slightly lowered at both locations.

The amount of carbon lost from the catchment (carbon load) is related to DOC concentrations and the total amount of runoff generated by rainfall events. Pre-restoration, carbon loads ranged between 3 and 264 kg in the monitored events, where average loads were 30.6 and 76.4 kg at Aclands and Spooners, respectively (Figure 22B). The reduction in rainfall in the years monitored post-restoration (as described in the Exmoor hydrology

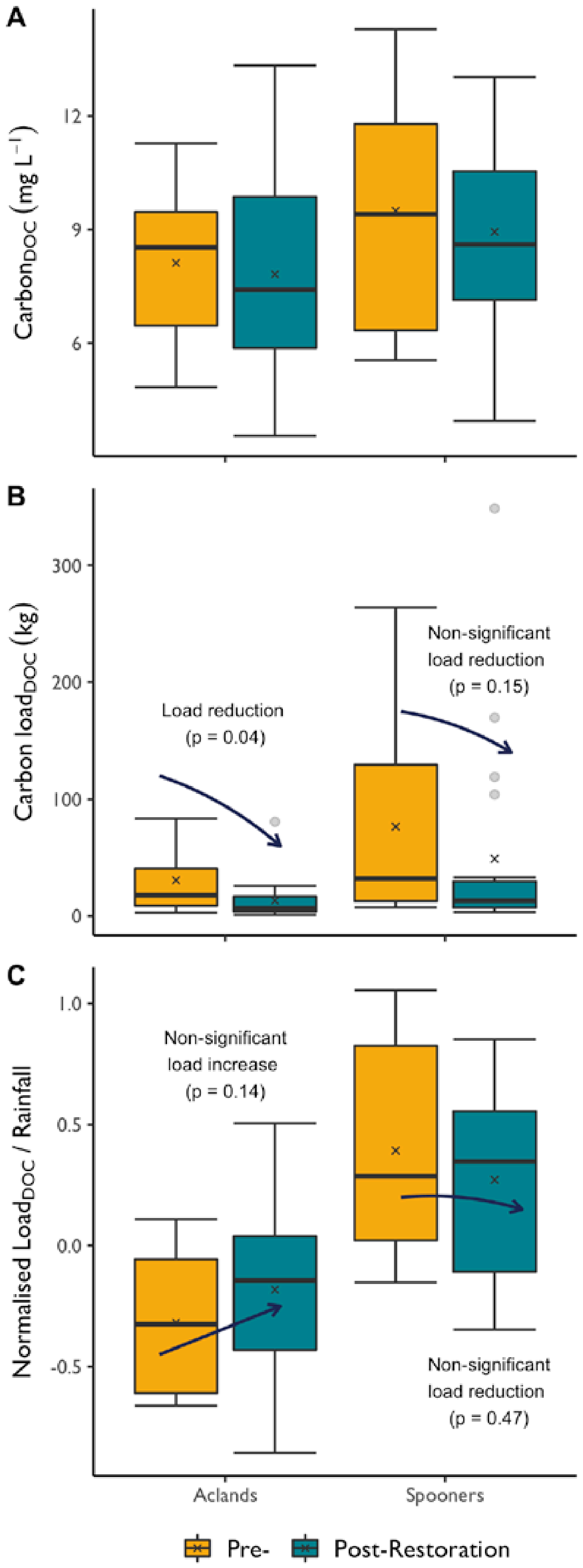

Figure 22 Observations at the flumes during monitored rainfall events A) flow-weighted mean dissolved organic carbon (DOC) concentrations B) total mass of DOC exported rainfall event, and C) Normalised (Log_{10}) relationship between DOC Load and rainfall to account for differences in rainfall pre and post-restoration. 'x' marks the average (mean) value, 'o' indicates observations that are considered outliers.

Looking downstream from Aclands flume towards the River Barle.

section, Figure 15) means that a significant decrease in DOC loads at Aclands (p=0.04), and a non-significant (p=0.15) decrease at Spooners (Figure 22B) were observed, with average post-restoration loads of 48.9 and 13.2 kg, respectively. This change becomes non-significant at both Aclands and Spooners when normalised for total event rainfall (Figure 22C). Normalising for rainfall allows the changes in load to be considered irrespective of the variation in rainfall for pre- and post-restoration monitored events. Positively, this indicates that restoration activities have not contributed to a significant increase in DOC loads. However, it does illustrate that a longer post-restoration period is needed to see if reductions in DOC concentrations can be achieved in these degraded moorlands.

In the short-term restoration has not had a statistically significant effect on the colour of the water (as measured by UV-Vis spectrometry at 400 nm) leaving the catchments (Figure 23A). Both catchments discharge water colour which remains above the European Commission standards (Abs^{400} of 1.5 Au m^{-1})[2].

The colour to carbon ratio (Colour$_{Abs400}$/Carbon$_{DOC}$) and the Specific Ultra-Violet Absorbance (SUVA -Abs^{254}/DOC) are useful tools for understanding the chemical characteristics of the DOC, which can then be used to infer the type of carbon being lost (e.g. from the decomposition of fresh plant material over that from more humified peat). Neither changed significantly post-restoration at Spooners (Figure 23B and C). In contrast, there was a significant change in both parameters in the Aclands catchment post-restoration. The results suggest that post-restoration the more humified peat (i.e. old peat) remains the primary source of the DOC leaving the catchments during rainfall events, rather than a shift towards DOC arising from fresh material as observed on Dartmoor (see next section). Further research is needed to attribute the significant changes observed at Aclands more robustly, which could be linked to the disturbances caused by restoration efforts, a change in the source of the DOC, or alterations to flow routing through the catchment.

If the vegetation communities change in response to restoration works, as is likely if higher and more stable water tables can be achieved and/or through *Sphagnum* re-introduction programs, it is expected that the amount and chemical characteristics of the DOC will change; DOC would be sourced from fresher material, as seen on Dartmoor (see next section). Importantly, this should also result in changes to the colour of the water leaving the catchments.

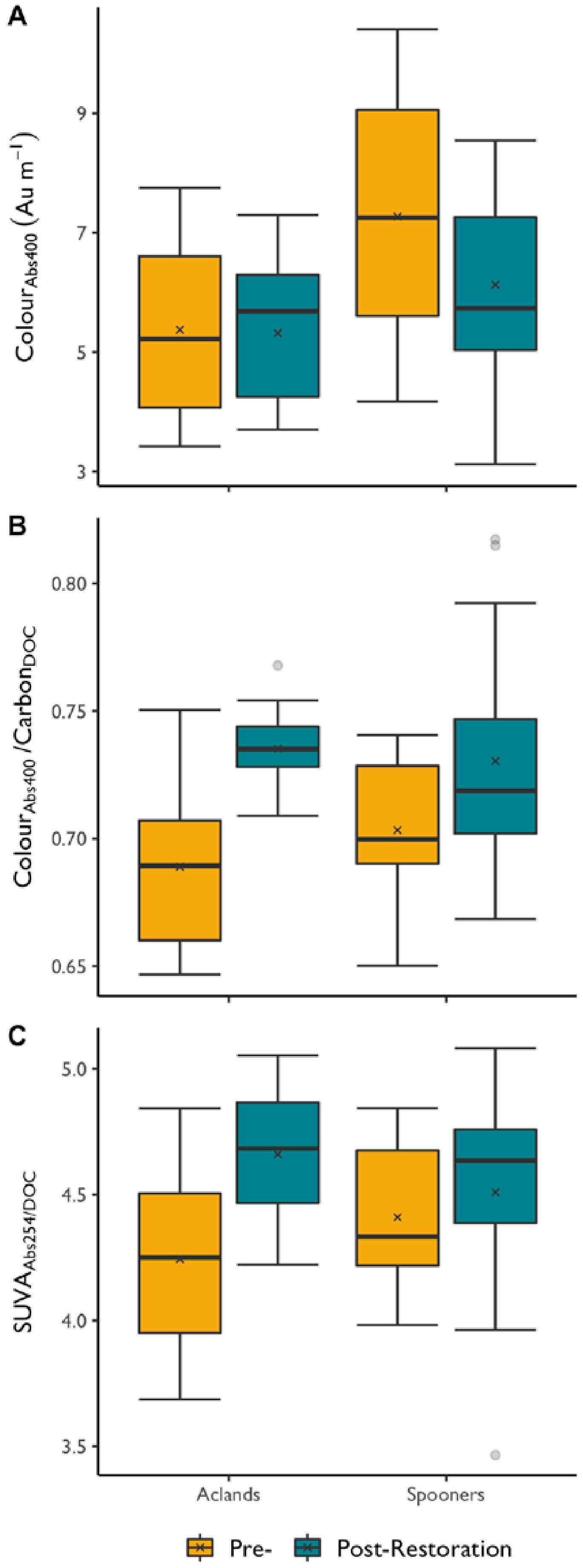

Figure 23 **A) average water discolouration (Abs400), B) average Colour per unit Carbon relation (Colour$_{Abs400}$/Carbon$_{DOC}$), and C) Specific Ultra-violet Absorbance (SUVA – Abs$_{254nm}$/DOC), observed during monitored rainfall events at the flumes pre- and post-restoration. 'x' marks the average (mean) value, 'o' indicates observations that are considered outliers.**

Figure 24 **Discharge monitoring at Spooners catchment.**

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How does restoration effect dissolved organic carbon run-off from a deep, eroding blanket bog?

- Post-restoration, the total load of dissolved organic carbon leaving the mire during monitored storm events was roughly 1/3 of the pre-restoration loads.
- Restoration had no statistically significant effect on dissolved organic carbon concentrations or water colour.
- Chemical characteristics of the water (C_{Abs400}/C_{DOC}, SUVA) changed significantly post-restoration suggesting a shift in the source of dissolved organic carbon to fresher organic matter.
- Restoration caused a step-change in hydrological connectivity; post-restoration, dissolved organic carbon took longer to reach the sampler as either sources were further away, transport was slower and/or pathways more tortuous.

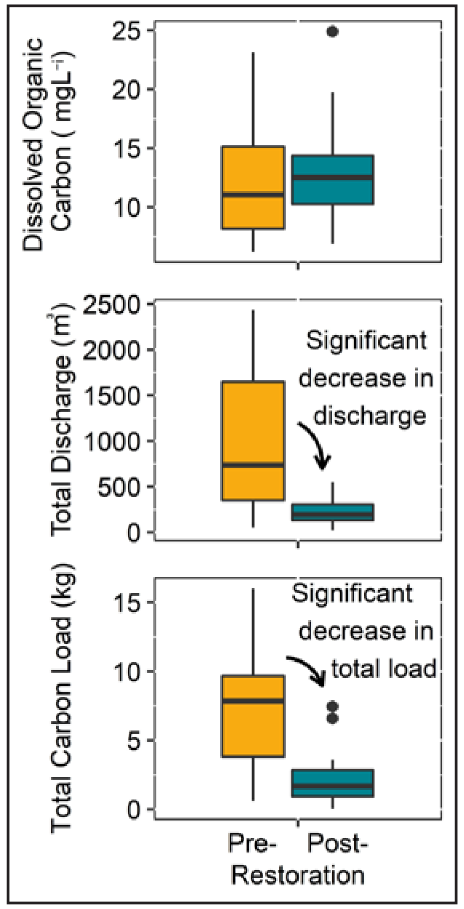

Figure 25 **Despite no significant effect of restoration on dissolved organic carbon concentrations (p=0.694) (top), a significant reduction in total sampled event discharge (middle) results in a significant decrease (p=0.001) in total cumulative carbon load (bottom).**

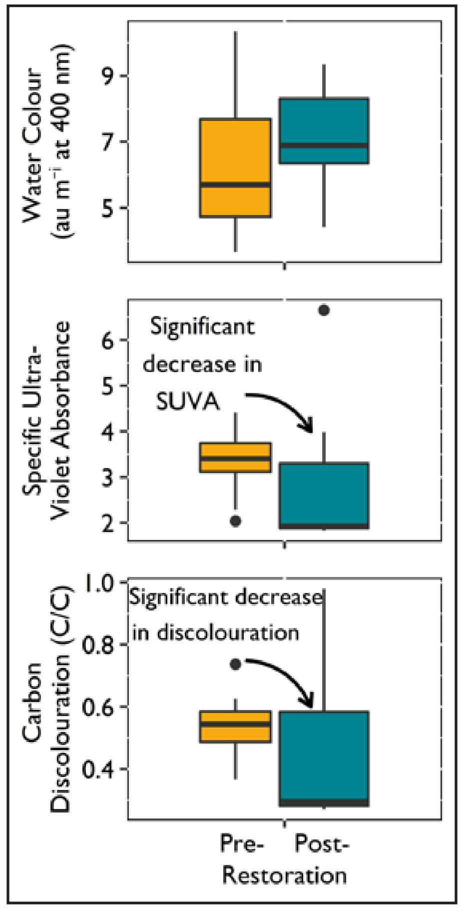

Figure 26 **Restoration had no effect on water colour (p=0.522) (top) but significantly decreased specific ultra-violet absorbance (p=0.011) (middle) and carbon discolouration (p=0.048) (bottom) suggesting a fresher source of organic carbon post-restoration.**

Rain falling on peatlands and flowing into rivers is a vital drinking water source. In their current state, organic carbon is being flushed from peatlands and carried downstream. As this dissolved organic carbon reacts with disinfectants to produce carcinogenic by-products, South West Water has a statutory duty to remove organic carbon in drinking water[1] at the Water Treatment Works. Restoration aims to improve ecological functioning of the peatlands; reducing the production of dissolved organic carbon at the source and therefore the total volumes reaching Water Treatment Works.

Water samples collected during storm events pre-restoration had dissolved organic carbon concentrations from 6.2 to 23.1 mg L^{-1}. This was similar to concentrations found on Exmoor (4 to 21 mg L^{-1})[2] but lower than more northerly peatlands (20 - 62 mg L^{-1})[3] heightened levels of degradation in response to environmental change have resulted in an increased loss of dissolved organic carbon (DOC).

Up to 3-years post-restoration there was no significant decrease (p=0.694) in dissolved organic carbon concentrations (6.9 to 24.9 mg L^{-1})[4] (Figure 25 top). Although the carbon concentration did not change post-restoration, the volume of water flowing though the gully decreased (Figure 25 middle) and therefore the total load of carbon being exported during monitored storm events was significantly (p=0.001) lower (Figure 25 bottom).

Restoration had no significant effect (p=0.522) on water colour (Abs^{400}) (Figure 26 top), however, the carbon in the water was significantly paler (p=0.048) (decrease in C_{Abs400}/C_{DOC}) (Figure 26 bottom) and more hydrophilic (p=0.011) (decrease in Specific ultra-violet absorbance (Abs^{254}/DOC)) (Figure 25 middle) suggesting a shift towards carbon from fresh plant litter, as opposed to release of deeper and older carbon within the peat soil (Figure 27).

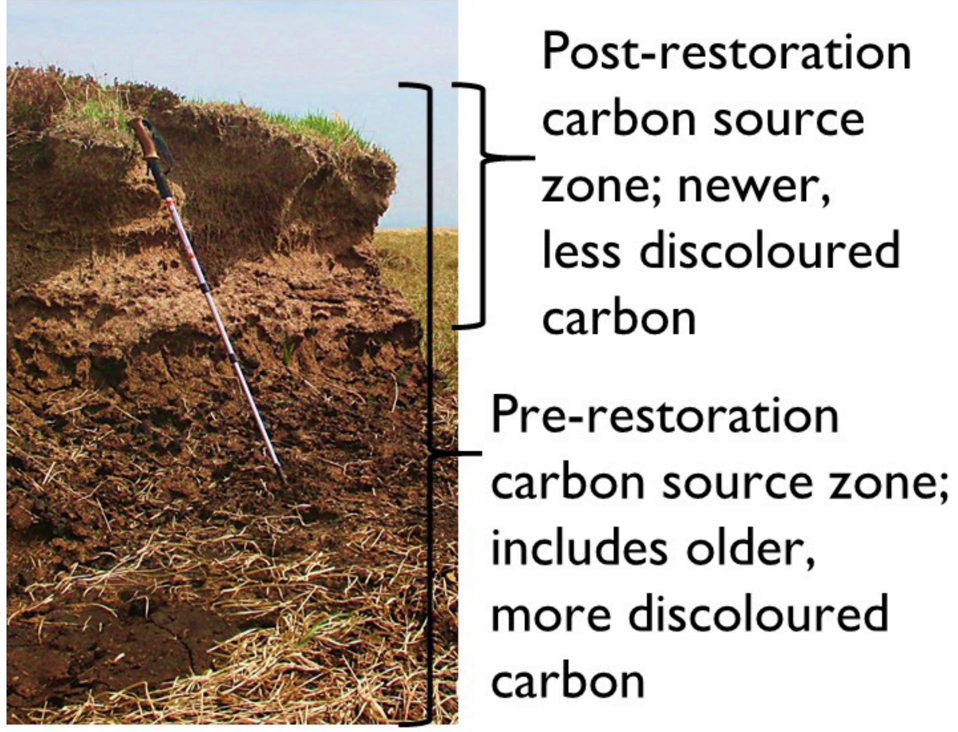

Figure 27 **A change in water chemistry suggests a shift in the dissolved organic carbon source post-restoration to paler, more hydrophilic, fresher organic material.**

The change in dissolved organic carbon concentration over time during a storm event (hysteresis index)[4] suggests a step-change in the hydrological connectivity (Figure 28). In a degraded mire, at the onset of rain, rapid surface/subsurface flow transports carbon from the degraded peat into the gully. As the rainfall continues these sources are depleted leading to dilution. Post-restoration dissolved organic carbon concentration increased over the storm, suggesting carbon sources were more distant, pathways were longer or transport slower. Post-restoration rainfall raised the water level in the pools until they overflowed (Figure 29). This overland flow, together with slower subsurface flow transported dissolved organic carbon to the gully later in the storm.

Figure 29 **Slower overland flow occurring above the water quality monitoring location (at base of the tube in the foreground) post-restoration. A wooden dam is visible in the foreground.**

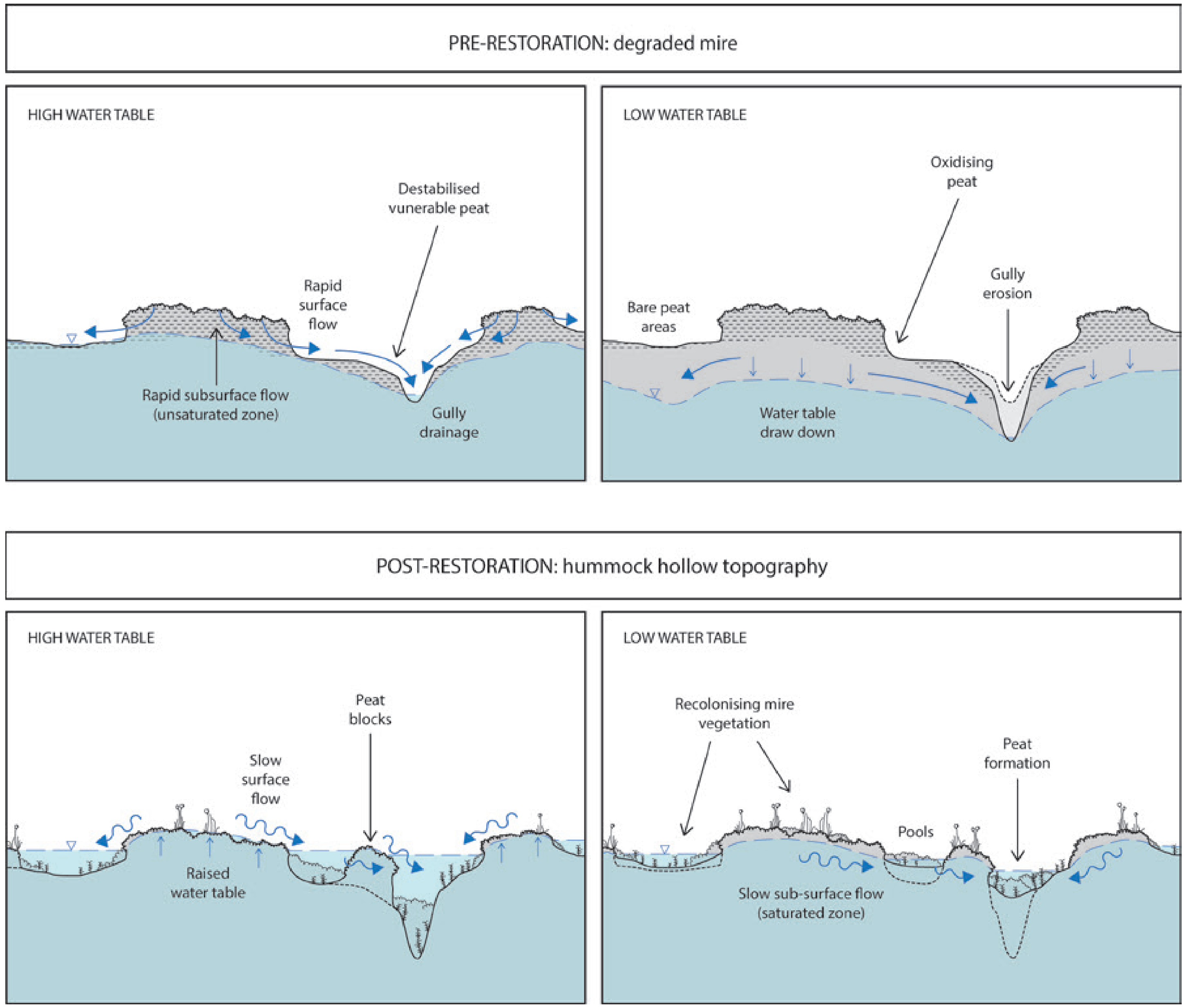

Figure 28 **Conceptual model of dissolved organic carbon production and transport pre- and post- restoration.**

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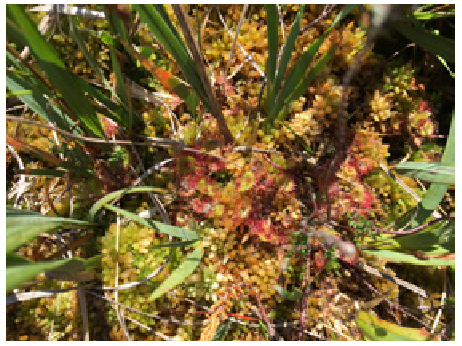

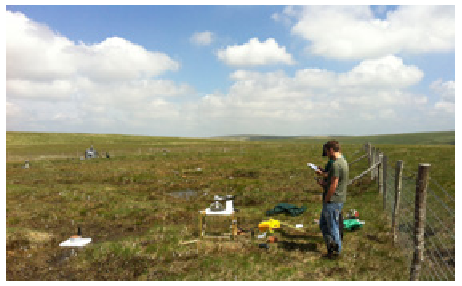

The grazing value of mires: How might restoration affect agricultural productivity?

- The nutritional quality of purple moor grass (*Molinia caerulea*) declines between spring and autumn whereas species characteristic of intact mires (bilberry (*Vaccinium myrtillus*), heather (*Calluna vulgaris*) and bog asphodel (*Narthecium ossifragum*)) maintain relatively high nutritional quality.
- Population densities of the sheep tick, a vector of economically important livestock diseases, are significantly lower in mires than in drier habitats on the same sites.
- Cattle spend little time in either degraded or restored mires, and so restoration should have a negligible effect on the area used for grazing.
- Restoration should have a minimal impact on the overall grazing value of a site.

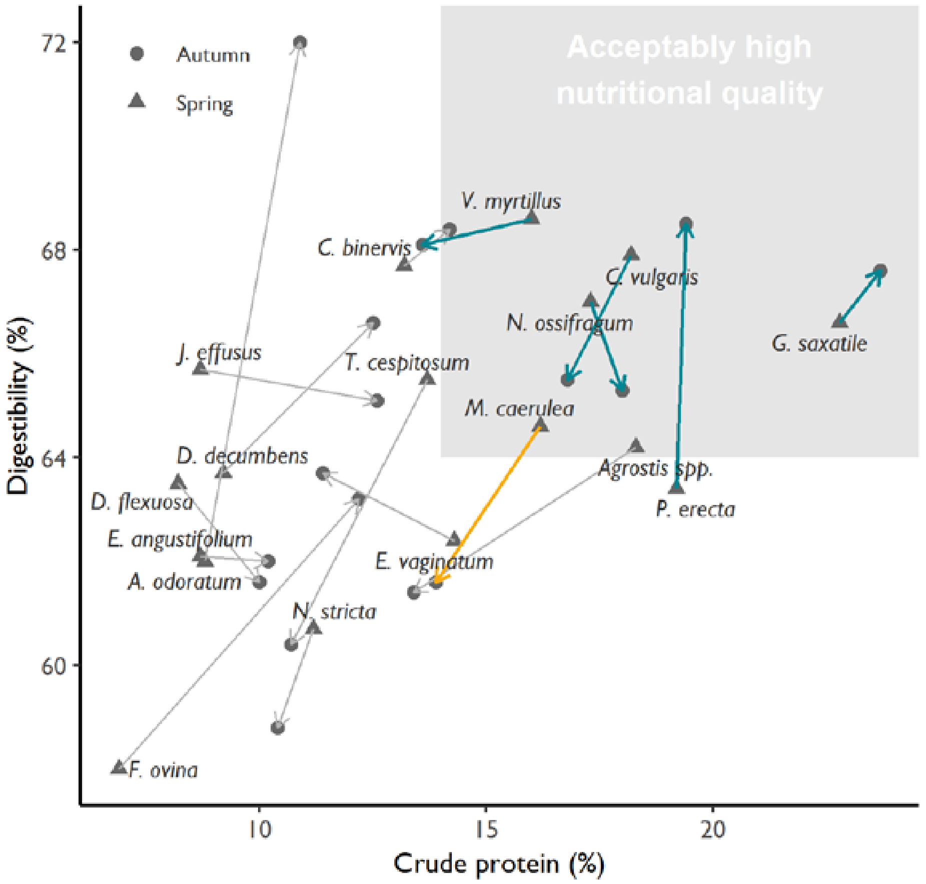

Figure 30 Changes in digestibility and crude protein (%), measures of nutritional quality, in the spring and autumn for a range of moorland plants grazed by livestock.

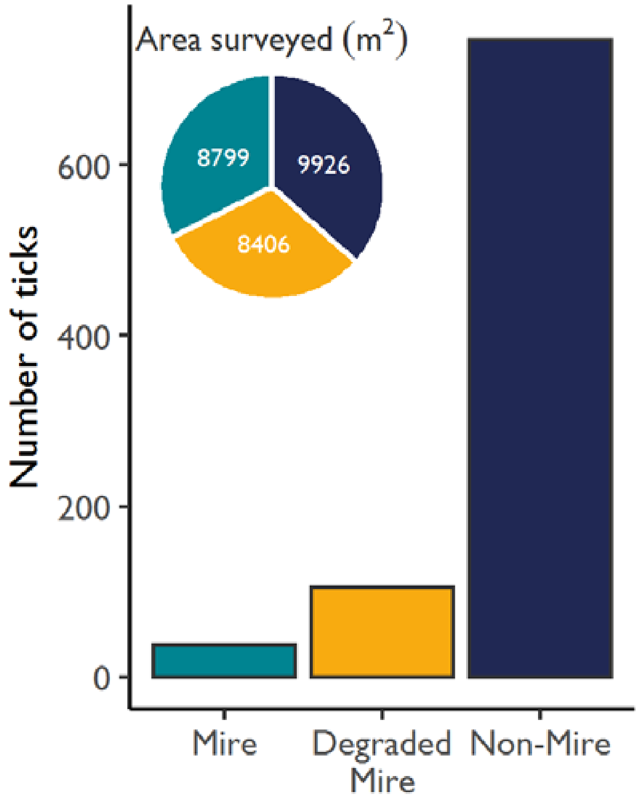

Figure 31 Number of ticks found within grouped habitat types and proportion of the surveyed area assigned to each habitat type, where 'Mire' consists of transitional and blanket bog, 'Degraded Mire' for areas dominated by purple moor grass (*Molinia caerulea*), and Non-Mire for areas including bracken, dry grassland and rush.

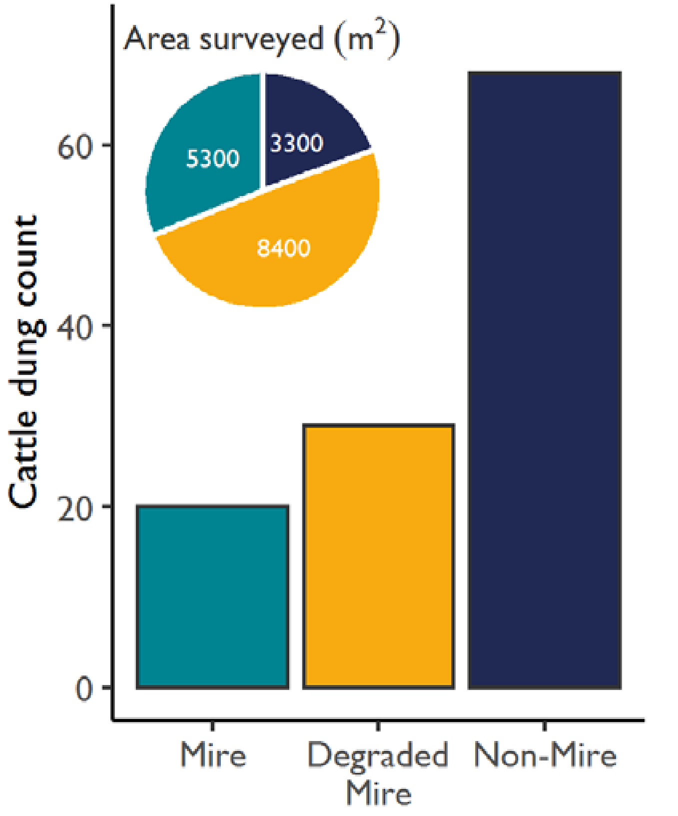

Figure 32 Number of cattle dungs, a proxy for level of use by cattle of each grouped habitat types and proportion of the surveyed area assigned to each habitat type, where 'Mire' consists of transitional and blanket bog, 'Degraded Mire' for areas dominated by purple moor grass (*Molinia caerulea*), and Non-Mire for areas including bracken, dry grassland and rush.

Restoration is expected to drive change in the vegetation communities of Exmoor's mires, and as these lie within areas used for grazing it is important to establish what effect these changes might have on the productivity of livestock farming.

This study[1] assessed the grazing value of degraded and restored mires, as well as other typical upland vegetation communities, such as rush pasture and bracken-dominated valley sides. The value of each vegetation type was based on three key factors: nutritional quality, prevalence of sheep ticks (vectors of livestock disease) and level of use by grazing cattle.

The nutritional quality of a plant is determined by a number of different measures, but particularly important from a grazing perspective are crude protein and digestibility, which affect, among other things, how rapidly an animal can gain weight. Levels of crude protein and digestibility were measured in 17 species of moorland plants associated with habitats of varying wetness (Figure 30). There was little difference in the overall nutritional quality of habitats, but there were seasonal changes in the relative quality of individual plant species, including purple moor-grass (*Molinia caerulea*) – the dominant species of degraded mire – which showed a sharp decline between spring and autumn. In contrast, the quality of species such as bilberry (*Vaccinium myrtillus*), common heather (*Calluna vulgaris*) and bog asphodel (*Narthecium ossifragum*), which are characteristic of recovering and intact mire, remained relatively high in both seasons. This suggests that rewetting areas of mire could increase the value of a site for livestock, as the associated increase in plant diversity ensures that the animals have access to vegetation of acceptably high nutritional quality throughout the grazing season.

Neither prevalence of sheep ticks (Figure 31) nor level of use by cattle (Figure 32) differed significantly between degraded and restored mires. Grazing cattle generally avoided areas of mire and instead showed a strong preference for drier, partially improved grasslands (Figure 32), although the value of these was diminished by the fact that they support far higher densities of sheep ticks than areas of mire (Figure 31). However, as the effects of rewetting are concentrated on areas of degraded mire, these findings would suggest that restoration will have a minimal impact on the overall grazing value of a site.

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EXMOOR | SHALLOW PEAT TOXIC FLORA

Bog asphodel distribution following peatland restoration on Exmoor

Figure 33 A cluster of bog asphodel (*Narthecium ossifragum*) flowers on Aclands July 2017.

- Post-restoration bog asphodel (*Narthecium ossifragum*) continues to survive but has not spread significantly.
- Bog asphodel contributes up to 20 % forage value in transitional bog habitats.

Bog asphodel (*Narthecium ossifragum*) is a common component of blanket bog vegetation, seen as patches of bright green fleshy leaves growing from patches of rhizomes (underground stems), with conspicuous yellow flowers in early summer[1](Figure 33). The leaves and especially the flowers are readily eaten by grazing livestock but contain toxins that can cause acute photosensitization and fatal liver and kidney disease in lambs and calves[2,3]. This research aimed to address concerns that restoration would increase the occurrence of bog asphodel and consequently livestock fatalities.

The plant height varies from 10 to 40 cm depending on the density of the surrounding vegetation and possibly on early season grazing. Growth and flowering rates vary significantly year on year and may account for the annual variations in toxicity seen in northern UK and Scandinavia.

Bog asphodel has a life history strategy that enables it to thrive in conditions intolerable to many plants i.e. very wet, acidic and nutrient poor soils[4]. It spreads only slowly by rhizoidal growth and does not rely on seed dispersal for survival. It does however persist in the most challenging conditions. Analysis of its distribution at individual sites and over 18 restored sites on Exmoor suggests it continues to survive following peatland restoration, but has not spread significantly in the short-term (<11 years) (Figure 34), as predicted by its life history strategy[5].

Bog asphodel leaves and flowers are a relatively nutritious component of transitional blanket bog habitat, comprising up to 18 % of forage value (Figure 35). This contribution may continue throughout the season, and its contribution to habitat crude protein value may even increase in the autumn.

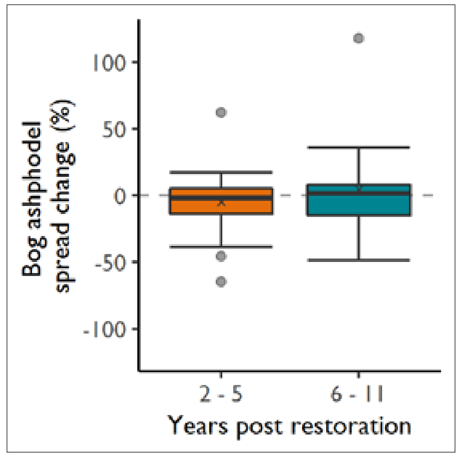

Figure 34 Post-restoration change in spread of bog asphodel (*Narthecium ossifragum*) over 18 sites on Exmoor. The x represents mean change (4.5±33.8 % 6 to 11 years post-restoration).

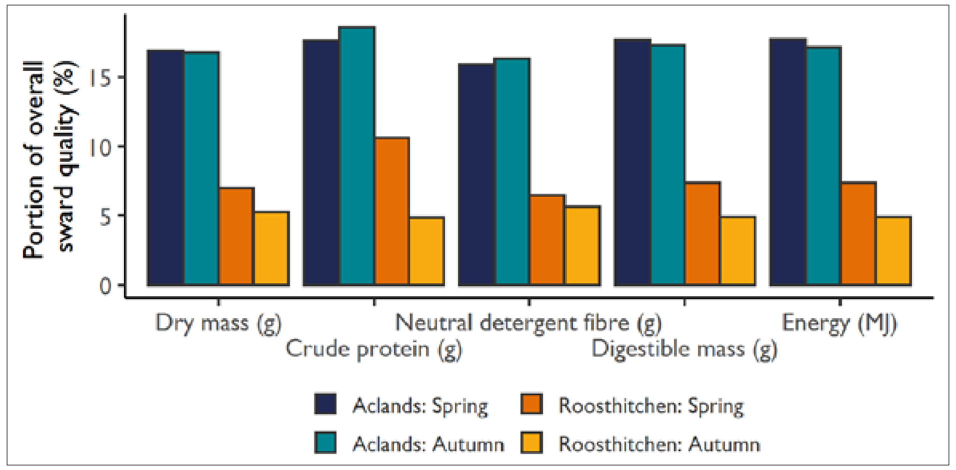

Figure 35 Bog asphodel (*Narthecium ossifragum*) forage quality at Aclands and Roosthitchen. Aclands (70 % bog asphodel cover) shows a steady 15-17 % contribution on 5 measures of quality, in both seasons. There was less bog asphodel at Roosthitchen (18 - 30 %) and this contributes 5 – 10 % on 5 measures of quality, less in autumn than spring. Energy represents metabolisable energy (MJ).

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EXMOOR | SHALLOW PEAT METHANE EMISSIONS

How does restoration age, vegetation and water depth impact methane (CH_4) emissions from restored mires within Exmoor National Park?

- Re-establishment of mire vegetation associated with wetter conditions serves as a useful indicator for increased CH_4 emissions, which in turn indicates that restored mires on Exmoor are returning to a more natural state.
- Annual CH_4 emissions from restored sites on Exmoor are low, even after ~7 years post-restoration, suggesting that the timeline for mire restoration to a more natural state is likely to exceed 10 years.

This study[1] investigated the gaseous carbon (C) balance of restored mires in Exmoor National Park using a restoration age sequence of sites (from 6 months to ~7 years post-restoration), as well as unrestored and semi-natural sites.

Increased cover of plants associated with wetter conditions (e.g., *Sphagnum* moss) and higher mean annual water levels were linked to increased methane (CH_4) emissions and site restoration status (Figure 36 and 37). Higher CH_4 fluxes indicate the presence of anaerobic (oxygen deficient) microbial communities where microbial CH_4 generation (methanogenesis) occurs as a biproduct in the breakdown of organic matter. Therefore, CH_4 emissions, and thus methanogenesis, is an indicator that anaerobic conditions are becoming more dominant within the peat soil due to increased water saturation.

Restoration activities on Exmoor seek to increase water saturation levels within the peat soils, and therefore CH_4 emissions can be viewed as a sign of restoration success. Figure 37 shows that vegetation data, particularly percentage cover of mire species associated with wetter habitats, could provide a valuable tool for assessing CH_4 emissions and site conditions of restored mires.

Semi-natural sites (those with little or no impact from drainage and peat cutting) from this study showed similar properties (i.e. gas emission balance, depth profiles of dissolved gases and stable C isotope analysis) to natural peat soils elsewhere in Europe and North America. However, the semi-natural sites from this study are likely still in a state of transition, also supported by vegetation survey data. Recovering peat soils can transition through a stage of higher CH_4 emissions before lowering as the coverage of gas conductive (aerenchymatous) plant species (e.g. cotton grasses (*Eriophorum* spp.)) decreases, and conditions within the peat soil stabilise.

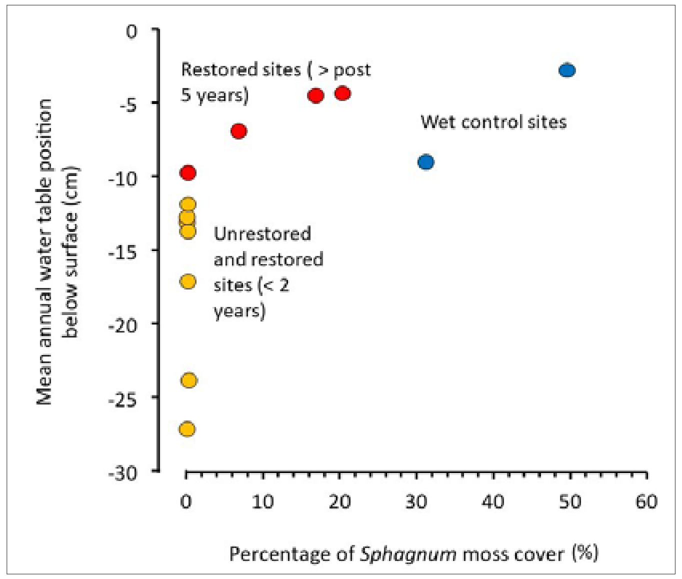

Figure 36 Mean annual water table position and percentage cover of *Sphagnum* moss for study sites ranging from unrestored and newly restored (yellow) through to semi-natural sites/wet controls (blue).

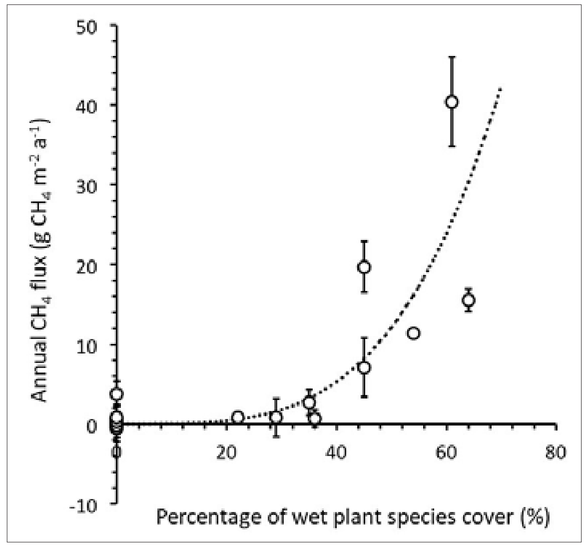

Figure 37 Relationship between annual methane (CH4) flux (g CH4 m^{-2} a^{-1}) and percentage (%) cover of wet mire plant species (e.g. *Sphagnum* moss) at sample sites. Flux estimates are based upon scaled monthly or bimonthly measurements from June 2013 to June 2014.

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How does ditch blocking in a shallow peatland affect emissions of carbon dioxide and methane in the short term?

- Wetter, *Sphagnum* spp. and cotton grass (*Eriophorum* spp.) dominated areas hold carbon for longer than drained, purple moor grass (*Molinia caerulea*) dominated areas.
- Where vegetation communities were completely dominated by purple moor grass (*Molinia caerulea*) they were not significantly altered by restoration in the short-term (<5 years).
- Restoration did not significantly alter photosynthesis (CO_2 drawdown), ecosystem respiration (CO_2 release) or below-ground (heterotrophic) respiration of the peat store.
- In the short-term (4-5 years) ditch blocking has not resulted in the high enough or stable enough water tables needed to promote the spread of *Sphagnum* spp. required to restore carbon sequestration.

Carbon dioxide monitoring.

Peatlands are the largest terrestrial carbon store. In a degraded state, peatlands lose carbon to the atmosphere and rivers, exacerbating the current climate emergency. Peatland restoration aims to raise and stabilise water tables. This promotes the growth of *Sphagnum* mosses required to shift the carbon balance towards carbon sequestration (drawdown and storage of carbon from the atmosphere).

Over the last 75 years, significantly greater ($p<0.039$) apparent rates of carbon accumulation (determined by Pb^{210} dating) were found in cores from a wetter, *Sphagnum* spp. and cotton grass (*Eriophorum* spp.) community compared to a drained, purple moor grass (*Molinia caerulea*) dominated community (Figure 38). The age of the peat at the bottom of the cores was younger than expected (ca.1920s) indicating long-term carbon storage is not occurring in these shallow peats. Despite this, the amount of carbon in the peat in the wet area (10.8±3.2 $kgCm^{-2}$) was double that of the dry area (4.6±0.4 $kgCm^{-2}$)[1].

Pre-restoration, the monitoring locations were dominated by purple

Figure 38 Greater apparent rate of carbon accumulation ($gC\ m^{-2}\ yr^{-2}$) for all ages of peat in cores from a wet (*Sphagnum* spp. and *Eriophorum* spp. community) compared to a dry (*Molinia caerulea* dominated community).

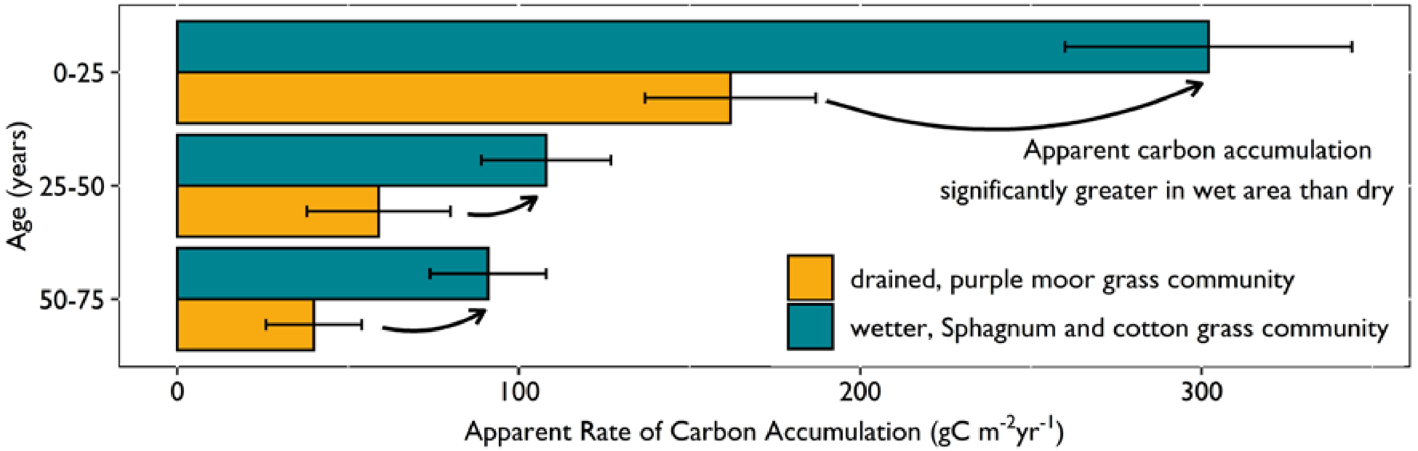

Figure 39 Greenhouse gas monitoring locations (foreground) within Aclands catchment.

Aclands' drainage ditches visible in the distance.

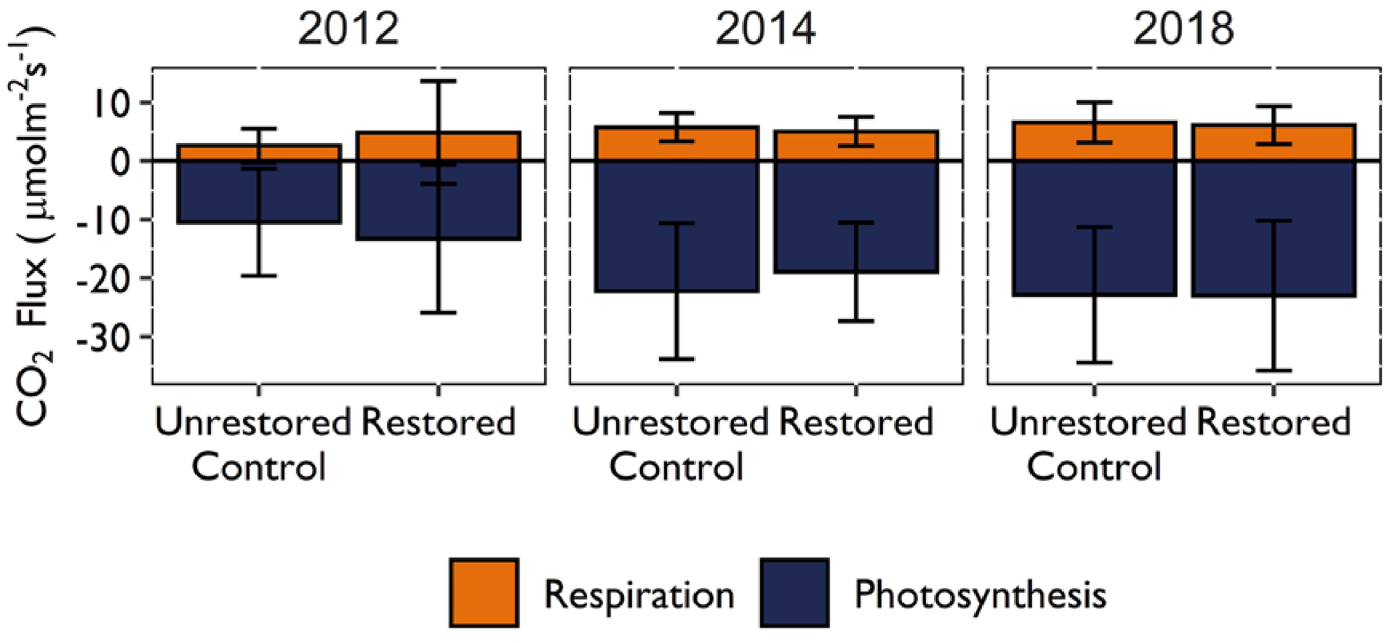

Figure 41 **Growing season photosynthesis (CO_2 drawdown) and respiration (CO_2 release) (µmol $m^{-2}s^{-1}$) pre- (2012) and post- (2014 & 2018) restoration showing no significant effect of restoration.**

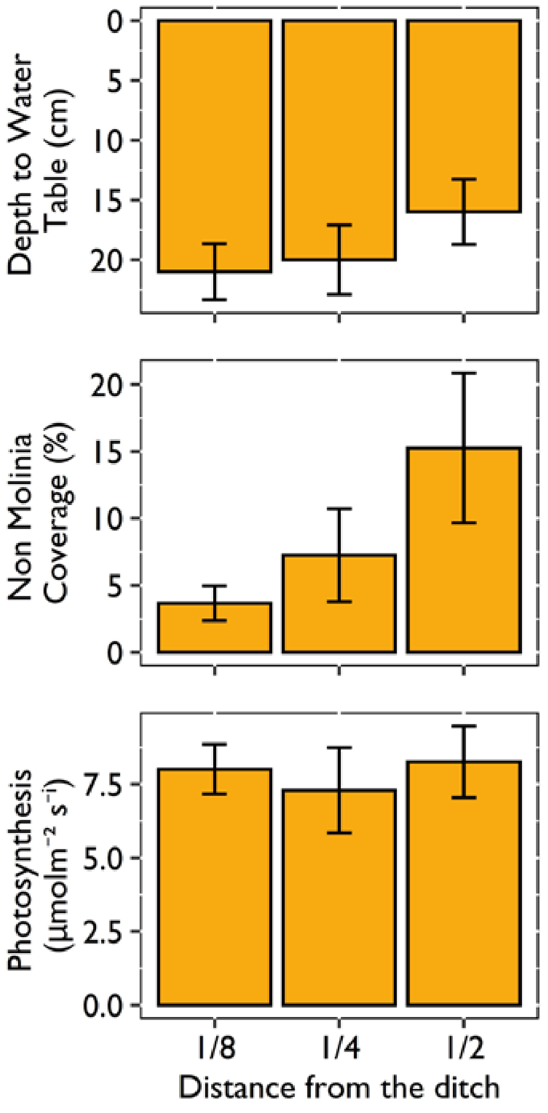

Figure 40 **Closer to the ditch water tables were deeper and vegetation diversity (non-*Molinia*) lower but this did not result in a clear pattern in photosynthesis (CO_2 drawdown).**

moor grass (*Molinia caerulea*) (86 ± 3 %)[2], representative of the wider catchment (Figure 39). Non-*Molinia* species coverage was significantly greater (p<0.024) and photosynthesis significantly less (p=0.034) where water tables were higher (wetter conditions). Although instantaneous water tables tended to be lower closer to the ditch (Figure 40), this pattern was not significant (p=0.197)[2].

Photosynthesis (CO_2 drawdown) significantly decreased during cooler and wetter periods (p=0.002) reflecting poor growing conditions[3]. As a result, the cool and wet summer of 2012 was modelled as a smaller CO_2 sink (126 gCO_2m^{-2}) than subsequent growing seasons (146 and 234 gCO_2m^{-2} in 2013 and 2014 respectively)[3].

Unfortunately the pre-restoration period (2012), was unusually wet (1901mm) and 2018 unusually dry (958 mm) with 2014 (1098 mm) and 2016 (1108 mm) intermediate (see Figure 15). This meant that at the sites studied, water tables fell following restoration due to drier climatic conditions. Allowing for climatic variability by comparing control and restored locations showed restoration had no significant effect on water tables (p=0.369)[4].

There was no significant change in purple moor grass (*Molinia caerulea*) coverage (p=0.855), non-*Molinia* coverage (p=0.387) or species richness (p=0.746) 4-5 years after restoration[4]. Consequently, there was no change in photosynthesis (CO_2 drawdown) (p=0.109, Figure 41), respiration (CO_2 release) (p=0.471, Figure 41) or below-ground (heterotrophic) respiration of the peat store (p=0.292).

Significantly more methane (p=0.039) was being oxidised at the restored sites than the control sites (Figure 42) contrary to expectations, however, fluxes were small with most of the measurements (213 out of 242) below the level of detection (zero flux)[4]. This variation is most likely due to initial differences in vegetation composition rather than restoration.

In the short-term (<5 years), ditch blocking in these shallow peatlands has not delivered high enough and stable enough water tables required to protect the existing peat and perturb the existing *Molinia caerulea*-dominated ecosystem sufficiently to bring about the shift in vegetation community required to restore carbon sequestration. Additional restoration techniques, such as mowing of purple moor grass (*Molinia caerulea*) or *Sphagnum* re-seeding, may be required alongside ditch blocking, to restore carbon sequestration.

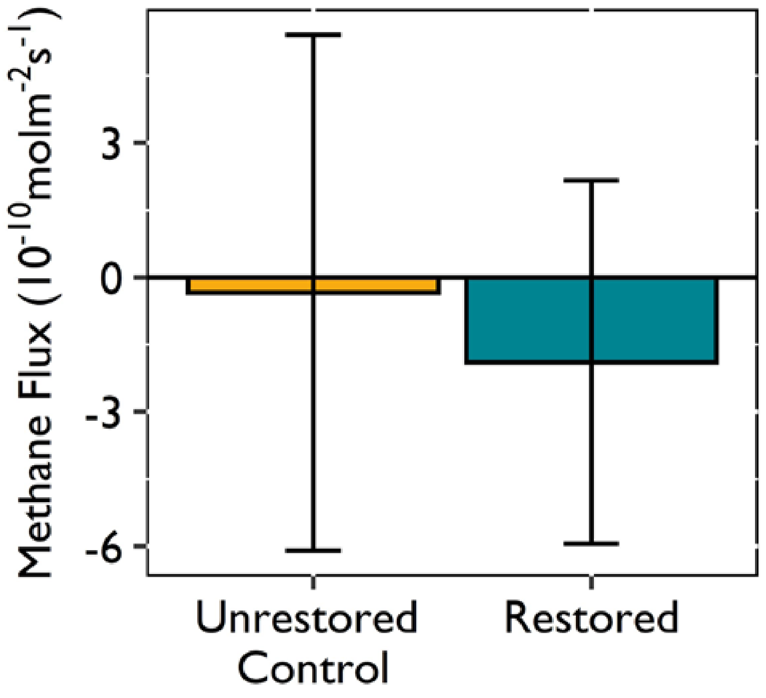

Figure 42 **Methane fluxes ($10^{-9}molm^{-2}s^{-1}$) over the summer of 2016 showing a more negative flux (oxidation) of methane from the atmosphere at the restored locations.**

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How does restoring erosional features over deep peats affect emissions of carbon dioxide and methane in the short-term?

- Degraded peatlands such as Flat Tor Pan are losing carbon as gaseous carbon dioxide from the visibly degraded bare peat areas and the surrounding vegetated areas.
- Water levels were significantly higher, the coverage of purple moor grass (*Molinia caerulea*) lower and cotton-grass (*Eriophorum angustifolium*) higher in restored vegetated sites.
- Restoration significantly reduced below-ground (heterotrophic) respiration of the peat store.
- In the short-term restoration had no significant effect on net ecosystem exchange but significantly increased methane (CH_4) emissions.

Dartmoor is estimated to store 13.1 mega tonnes of carbon[1] roughly equivalent to 10 % of the UK's greenhouse gas emissions in 2018[2]. High water tables in a healthy peatland prevent the complete decomposition of dead vegetation, allowing carbon to slowly accumulate. However, much of Dartmoor's peatlands are currently degraded[3] putting this carbon store at risk. Restoration offers the potential to not only protect the existing carbon store but also promote carbon sequestration to mitigate the current climate emergency.

Figure 43 Pre- and post-restoration at Flat Tor Pan showing the sparsely vegetated eroding pans between the vegetated haggs becoming pools.

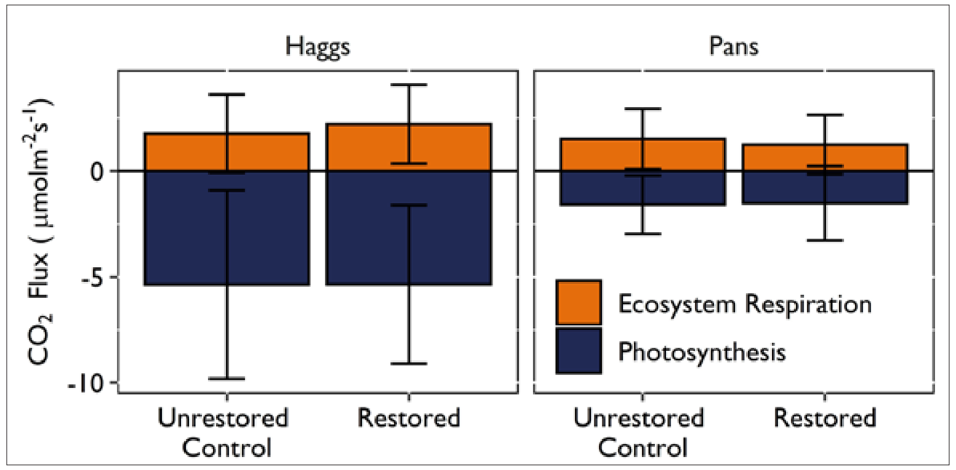


Figure 44 Photosynthesis (CO2 drawdown) and ecosystem respiration (CO2 release) from the haggs and pans at the unrestored control and restored locations.

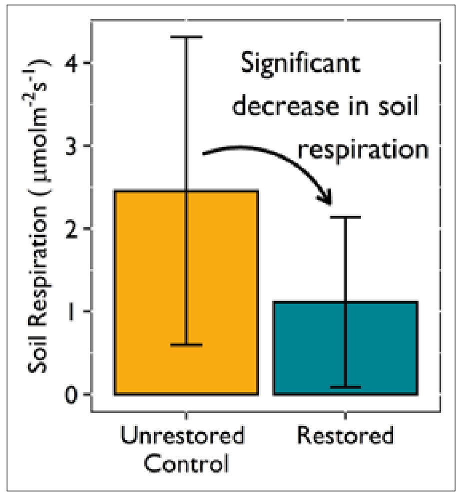


Figure 45 Significant reduction (p=0.001) in below-ground (heterotrophic) respiration of the peat soil at the restored location compared to the unrestored control.

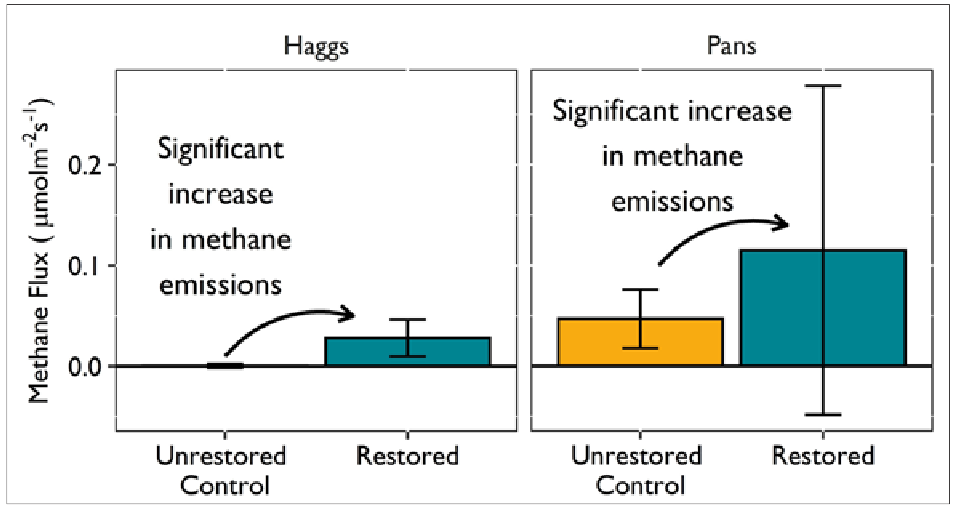
Pre-restoration the water table was lower but more stable in the haggs (9.1 ± 5.4 cm) than the pans (7.1 ± 10.1 cm)[4] causing substantial differences in vegetation coverage and composition (Figure 43). Consequently, carbon dioxide fluxes (photosynthesis in and ecosystem respiration out) were greater in the vegetated haggs than the pans. An empirically derived net ecosystem exchange model estimated that the haggs (29 and 20 gC m^{-2}) and the pans (7 and 8 gC m^{-2}) were growing season carbon sources for 2013 and 2014[4]. This suggests both the visibly degraded peat pans and the surrounding vegetated haggs are losing carbon to the atmosphere, highlighting the need for restoration.

Water table depths were higher in the restored locations than the unrestored control locations for both the haggs (2.0 cm restored; 9.3 cm control) and the pans (-11.8 cm restored; 8.9 cm control). In the unrestored control hagg sites, coverage of purple moor grass (*Molinia caerulea*) and bog cotton-grass (*Eriophorum angustifolium*) was significantly greater (p=0.036). No other significant differences were observed in the vegetated haggs or the peat pans. Wider vegetation monitoring across Flat Tor Pan (79 quadrats) also found significant decreases in purple moor grass (*Molinia caerulea)* and increases in bog cotton-grass (*Eriophorum angustifolium*) but also found *Sphagnum capilifolium* to decrease and *Sphagnum denticulatum* and *Sphagnum subnitens* to increase post-restoration[5]. Despite this (limited) vegetation change, net ecosystem exchange (the balance between photosynthesis and ecosystem respiration) was not significantly different between the unrestored control and restored areas (Figure 44)[6].

High water tables promote an oxygen free environment. This reduces the volume of oxygenated peat, limiting more rapid aerobic respiration, significantly reducing ($p<0.001$) (heterotrophic) respiration of the peat soil (Figure 45)[6]. Consequently, restoration reduced the carbon being lost from the peat store via this pathway.

However, high water tables also enable the production of methane by soil microbes (methanogens). Vegetation with hollow stems (aerenchyma) e.g. cotton grasses (*Eriophorum* spp.) allow methane to by-pass the oxygenated zone and diffuse directly to the atmosphere. Higher water tables and the presence of cotton grasses *(Eriophorum* spp.) in the restored locations have resulted in significantly ($p<0.001$) higher methane emissions (Figure 46)[6]. Over time it is expected that cotton grass (*Eriophorum* spp.) will be replaced by *Sphagnum* spp. which do not facilitate methane release. This change in vegetation composition would also shift the balance in organic matter production and decomposition towards a blanket bog that slowly accumulates carbon. Future monitoring is planned to test this hypothesis over the next 5 years.

Figure 46 Methane emissions at the restored and unrestored control showing significantly greater emissions ($p\leq0.001$).



Monitoring carbon dioxide and methane emissions.

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DARTMOOR

DEEP PEAT EXTENT AND CONDITION MAPPING

Detailed landscape-scale peatland mapping using airborne remote sensing data

- It is estimated that Dartmoor National Park has 158 ±101 km^2 (15800 ha) of peat >0.4 m deep storing 13.1 megatonnes of carbon[1].
- An area of 29 km^2 (2900 ha) or 9.2 % of the peat extent was identified as significantly and directly ecohydrologically degraded by erosional gullies, peat cuttings, drainage ditches and bare peat[2].
- Functionally intact blanket bog covers 3.6 km^2 (360 ha) or 0.8 %, however, it is fragmented and often surrounded by ecohydrologically degraded peat[3].
- The maps produced provide an unparalleled level of detail across the whole of the moorland (444 km^2, 44,400 ha) facilitating effective and targeted restoration planning, management and monitoring.
- An interactive map of the identified features and peat extent is available to view online (**https://maps.dartmoor.gov.uk/peatland.html**).

An erosion gully, Amicombe, Dartmoor.

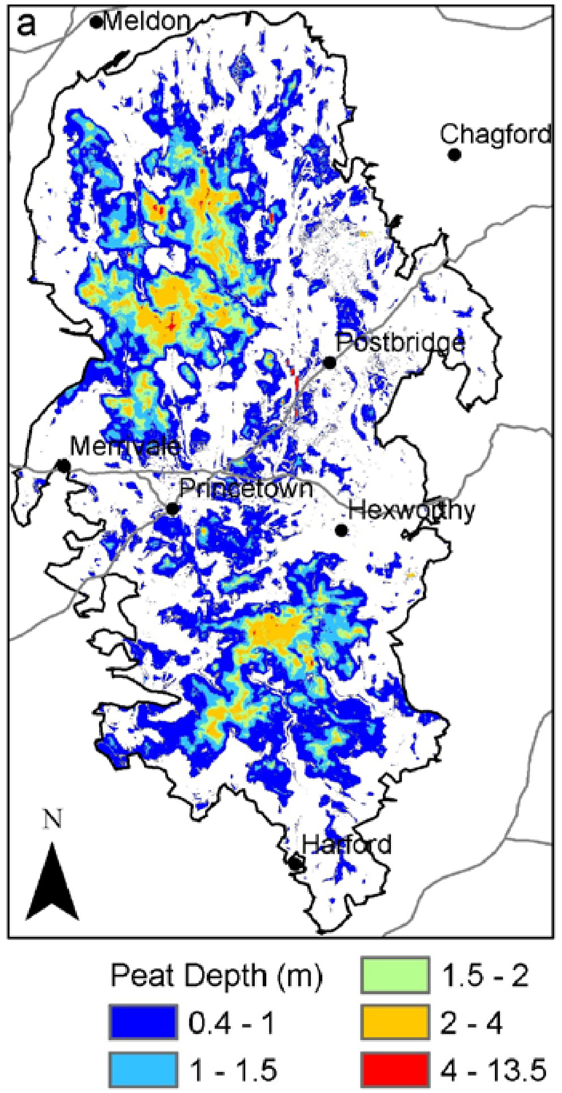

Figure 47 **Peat depth (metres) modelled across Dartmoor from airborne radiometric and LiDAR data.**

Dartmoor National Park Authority and South West Water commissioned the mapping of Dartmoor's peatlands to provide information about the extent and condition of the peat soil to facilitate effective and targeted restoration planning, management and monitoring.

A novel method was developed using airborne radiometric and LiDAR data to model peat depth and extent at an appropriate resolution (10 m) to facilitate landscape management. This model estimated Dartmoor to have an area of 158 ±101 km^2 (15800 ha) of peat >0.4 m deep (Figure 47) storing 13.1 megatonnes of carbon (8.1–21.9 Mt. C)[1]. Much of this area (60 km^2, 6000 ha) is overlain by grassland which would have been missed if vegetation cover was used to map peat extent.

Additionally, airborne LiDAR and aerial images (Red/Green/Blue spectra and Compact Airborne Spectrographic Imager) were combined (Figure 48) to identify and quantify land surface features contributing to, or as a consequence of peatland degradation including: anthropogenic drainage ditches and peat cuttings; erosional gullies and bare peat areas.

Peat cuttings (Figure 49) were found to cover an area of 26.6 km^2 (2660 ha) concentrated in the four main areas of historic commercial cutting (Rattlebrook Hill, Walkham Head, Blackbrook Head and Brent Moor) with some smaller zones in other more disparate areas of deep peat[2]. Drainage ditches, totalling 427 km in length, were recorded, closely spaced in areas of deep peat and often associated with peat cuttings[2]. Extents of bare/sparsely vegetated and vulnerable peat were found to cover a total area of 0.9 km^2 (90 ha). These areas were found to be predominantly located on flatter/convex parts of the landscape often with erosional gullies arising out of the dendritic complex. In total, erosional gullies were mapped as covering a total of 7.85 km^2 (785 ha). Combining multiple datasets to map these features has significantly increased our understanding of the spatial distribution and connectivity of these features within the landscape.

The mapped features are known to lower the water table in the adjacent peat and therefore have an effect beyond their bounds. To estimate such effects, modelled zones were applied to the mapped features, dependent on the type of feature and its position in the landscape to estimate the total ecohydrologically degraded area present. It is estimated that 29 km^2 (2900 ha) of the peatland extent is significantly and directly ecohydrologically degraded by drains, peat cuttings, erosional gullies and bare peat[3]. Finally, structural information and aerial imaging were used to identify areas of functionally intact blanket bog covering an area of 3.6 km^2 (360 ha). These areas were shown to be fragmented and often surrounded by ecohydrologically degraded peat[3]. Identifying features (erosional gullies, drains, cuttings and bare peat) that are proximal to these functionally intact bogs has enabled areas to be prioritised for restoration interventions.

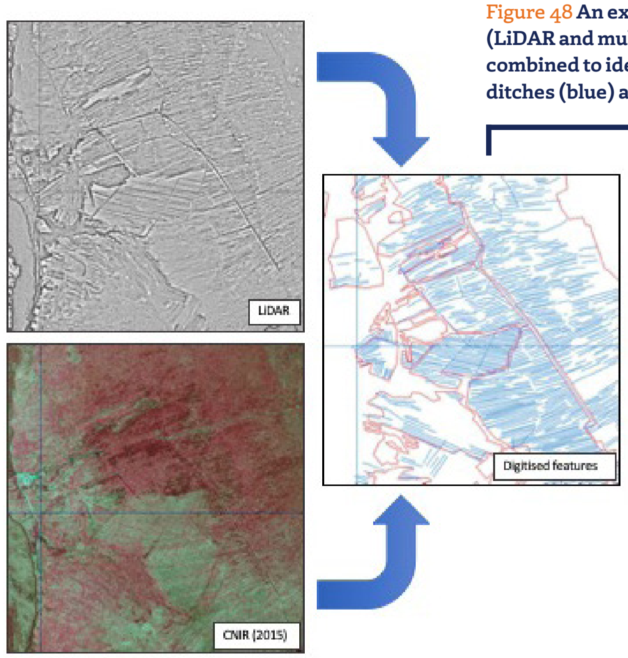

Figure 48 **An example of how multiple datasets (LiDAR and multispectral aerial images) were combined to identify anthropogenic drainage ditches (blue) and peat cuttings (red).**

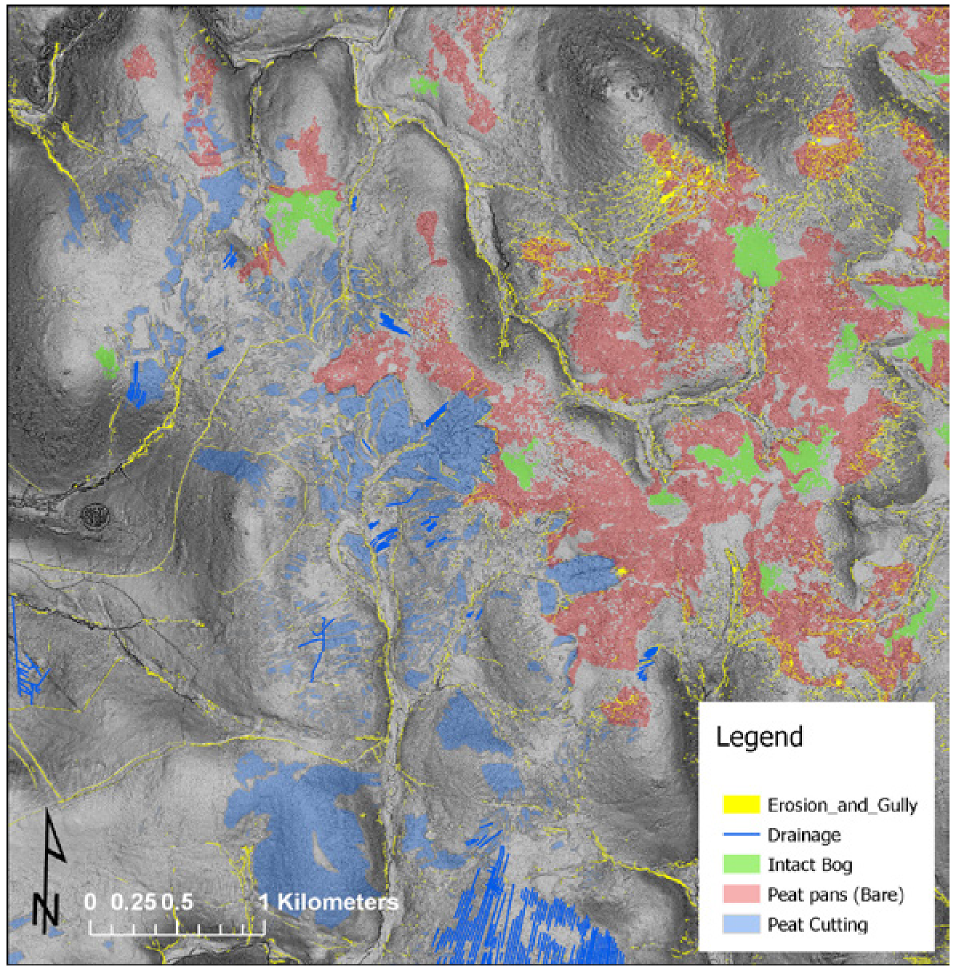

Figure 49 **Overview showing the mapped features across the Merrivale Range area on Dartmoor, demonstrating how features relate to each other within the landscape.**

REFERENCES

The appendices are available to view at **www.exeter.ac.uk/creww/research/casestudies/miresproject**

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Knowledge Gaps and Future Research

Research to date has focused on gaining an empirical understanding of the effects of restoration on a range of ecosystem services at the plot scale. Our findings so far, described in this document, inevitably lead to further questions that would benefit from scientific insight, for example:

- Peatland hydrology, dissolved organic carbon production and greenhouse gas emissions are strongly linked to vegetation composition, in particular *Sphagnum* recolonization. Changes in vegetation communities can be slow i.e. over decadal timescales. It would therefore, be beneficial to return to restored sites 10-years following restoration to see if, given more time, the effects of restoration have changed or are more pronounced.
- Previous work has quantified the effects of restoration during higher water flows, to understand changes in flood risk and the inputs to water treatment systems. However, peatland restoration may also increase river baseflows between rainfall events, providing other important ecosystem services and ecological benefits. Quantifying changes in baseflow would enable a fuller understanding of the effects of restoration on river flows from these restored peatlands.
- As ditch blocking in shallow peat has not universally brought about the change in vegetation required to alter dissolved organic carbon production or greenhouse gas emissions, different methods of *Sphagnum* reintroduction are being piloted. The costs and effects of these different methods could be assessed over the next few years to ascertain their differing effectiveness.
- Vegetation surveys have indicated that ditch blocking in shallow peat is more successful in some areas than others, as yet we do not understand why some areas respond better to ditch blocking than others. An improved understanding of this would enable restoration resources to be more effectively targeted in the future.

Moorland Scale Effects of Restoration

Further work is also required to combine the ground based empirical understanding with landscape extent remote sensing data to extrapolate this understanding to the moorland scale. For example, we have observed an average increase in deep water storage of 7.3 cm at Flat Tor Pan (see Dartmoor Deep Peat Hydrology). Given that an area of 6 km^2 was mapped as ecohydrologically affected by comparable peatland features (eroding peat pans, see Dartmoor Deep Peat Extent and Condition Mapping) we can already make broad assumptions as to the potential water storage Dartmoor could provide. In this example, assuming the peat has bulk density of 50 % (as a conservative estimate) and that this area was similarly restored, an additional 219 million litres of water would be stored within the peatlands of Dartmoor if they were restored. Future work could expand and improve such estimations, and better contextualise the effects of restoration across the landscape. Examples of opportunities include:

- Peat cuttings, unlike other types of degradation, do not always result in a change in vegetation cover and loss of peatland functioning. This may be because they are lower than the surrounding peat, act as a hydrological sink and therefore maintain locally high and stable water tables. A better understanding of which peat cuttings (type and location) require restoration and which do not would enable restoration resources to be more effectively targeted in the future.
- Current peatland mapping work has enabled us to understand where peat is degraded within Dartmoor National Park. Initial work using remote sensing data to optimise the restoration of complex degraded peatland systems has been invaluable to planning restoration. Extending and developing this preliminary work across larger extents and encompassing a wider range of degradation types (and restoration techniques) could provide a novel and detailed ability to optimise restoration across multiple landscapes.

GLOSSARY

Baseflow

The delayed subsurface flow into nearby streams and rivers, that results in discharge outside of rainfall episodes.

C_{Abs400}/ C_{DOC}

Colour per unit carbon. The ratio of colour, as measured by ultra-violet spectrometry at 400 nm, to dissolved organic carbon concentration.

DOC

Dissolved organic carbon (mg L^{-1}), measured by ultra-violet spectrometry.

Quickflow

Overland flow and rainfall runoff which reaches the river quickly and causes a rapid rise in stream flow.

SUVA

Specific ultra-violet absorbance, the ratio of the absorbance of ultraviolet light at 254 nm to dissolved organic carbon concentration. A proxy for hydrophobicity.

Water Table Depth (WTD)

The distance between the upper edge of the soil surface and the upper edge of the groundwater level, beneath the surface.

Deep water storage

The groundwater stored deep in the peat soil. Specifically, the water permanently stored below the level that groundwater levels fluctuate.

UAV

Unmanned Aerial Vehicle, also known as a drone.

Heterotrophic respiration

Respiration by non-plant (photosynthesising) organisms including those that decompose organic material in the soil/peat.

Mires On The Moors Project

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South West Water

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The Dartmoor Society
Department for Environment Food & Rural Affairs

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