Trajectories for impacts of re-vegetation activities on upland blanket bogs

Summary report

Prepared by

MOORS FOR THE FUTURE
PARTNERSHIP

2016

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Abstract

More than half of England's Sites of Special Scientific Interest (SSSI) are found in the uplands, designated for their outstanding wildlife habitats and unique species assemblages. Through its conservation work, Moors for the Future Partnership (MFFP) actively implements government strategies aimed at reversing the degradation of blanket bog habitat, particularly in the Dark Peak and South Pennines. Since 2003, frequent and detailed surveys by MFFP show the effect of conservation actions on the developing vegetative community and have become an important tool for Natural England to assess the condition of blanket bog SSSIs and in particular their progress towards Favourable Condition. While this goal is defined mainly by the diversity of the developing vegetative community, conservation actions also serve (amongst other changes) to prevent erosion and to reverse degradation of the hydrological regime, reducing flood risk and providing cleaner water.

The principal aim of this study therefore is to produce trajectories of progress in the diversity of blanket bog indicator species, in water table height, in the amount and timing of peak overland flow during storms, and also in various measures of water quality and sediment accumulation.

Trajectories for the development of three key attributes involved in achieving Favourable Condition status showed that the percentage of quadrats fulfilling the minimum requirements for extent of bare peat improved at a linear rate of 16 percentage points per year, before levelling off after about 5 growing seasons. For the cover and number of indicator species, the linear improvement extended over the whole 12 years covered by the surveys, although with relatively lower rates of 6 and 1.4 percentage points per year, respectively. The imminent use of *Sphagnum* propagules (containing 12 indicator species) in MoorLIFE 2020 is specifically aimed at raising these levels towards the 90% required to achieve Favourable Condition status.

Linear improvements in water table height were found in dipwells during manual campaigns and in automatically logged sensors, amounting to rates of 24 and 37 mm yr^{-1} respectively, over the full 12 years of surveying. A strong linear correlation between the cover of indicator species and height of water table suggested a potential role for vegetation and relatively slowly decomposing litter of indicator species altering evapo-transpiration processes at the soil surface. Application of *Sphagnum* in ML2020 is likely to improve this further.

Storm flow lag times (between peak rain input and peak flow output), the amount of peak storm flow and the hydrograph shape all showed a statistically-supported 'step-change' recovery in the first year. This is likely to be related to a threshold cover of vegetation surpassed in the first year, effectively 'slowing the flow' due to surface roughness. Treatment with densely-planted *Sphagnum* propagules to one of the mini-catchments is likely to cause further recovery.

Concentrations of calcium, a major component of the lime treatment, were significantly raised following treatment and were still elevated some 18 months after the final dose of three annual applications of lime starting at the time of the seeding. This was accompanied by significantly increased pH levels. Annual mean concentrations of Dissolved Organic Carbon (DOC) did not change as a result of treatment and changes to the composition of DOC were not clearly evident. There were no other effects found.

Gully blocks successfully trapped sediment during the first two years after installation but there were insufficient data available at the time of writing to show trajectories or to draw reliable conclusions as to the relative successes of each type of gully block.

The trajectories for vegetative diversity, water table height and storm flow were all positive, returning the system to a less degraded state. More time is required to show meaningful trajectories for water quality, free from the potentially confounding effects of treatment over the first three years. The widespread use of *Sphagnum* propagules in MoorLIFE2020 is likely to provide further improvements to the trajectories.

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1 Introduction

More than half of England's Sites of Special Scientific Interest (53%) are found in the uplands, designated for their outstanding wildlife habitats and unique species assemblages. Almost 90% of these upland SSSIs form part of the Natura 2000 series; sites regarded as having special significance in a European context. The European-legislated South Pennines Moors Special Area of Conservation (SPM SAC) is an internationally-recognised SAC, overlapping with many of the SSSIs of the Peak District National Park and South Pennines. These areas are particularly notable for containing one-third of the UK's blanket bog habitat; a habitat that is both globally rare (Britain holds between 10 and 20 % of the entire global resource) and also uniquely endowed with an assemblage of vegetation types that is internationally our most important (Lindsay et al 1988; Tallis 1995).

Blanket bog areas within the SPM SAC have suffered from a high level of degradation, mainly through the loss of peat-forming *Sphagnum* mosses which followed from historical and sometimes ongoing effects of pollution, in addition to wildfire, overgrazing and localised trampling. As a result these areas became characterised by extensive bare patches, while also being intersected by erosion gullies (reviewed in Buckler et al, 2013).

Building on the approach put forward in the Natural Environment White Paper (June 2011) and the England Biodiversity Strategy (August 2011), 'Biodiversity 2020' seeks to halt overall biodiversity loss, with targets to improve the condition of SSSIs by achieving 50% in Favourable Condition and 95% in Favourable or Recovering Condition by 2020, and for non SSSI priority habitats, such as blanket bog, 90% to be in Favourable or Recovering Condition (Natural England 2013)

Working alongside these targets, the principal aim of the Moors for the Future Partnership's (MFFP) conservation work is to 'conserve and reverse the degradation of blanket bog habitat in the Dark Peak and South Pennines, working towards the re-creation of active blanket bog, with an active *Sphagnum*-based acrotelm, and dominant surface vegetation based on the NVC community M19 *Calluna vulgaris-Eriophorum vaginatum* blanket mire *Empetrum nigrum* ssp. *nigrum* sub-community' (Buckler et al, 2013).

However, current assessment of condition status in SSSIs by Natural England may not of a sufficient detail or temporal resolution to show the effect of conservation actions and management in making progress towards Favourable Condition. Therefore the aim is to produce a trajectory matrix which estimates the timescales required to deliver Favourable Condition. This report brings together and summarises five reports on the effect of conservation works on key parameters of change:

Annex 1: Vegetation

Annex 2: Water table

Annex 3: Water flow

Annex 4: Water quality

Annex 5: Sediment accumulation

2 VEGETATION TRAJECTORIES (SUMMARISED FROM ANNEX 1)

Monitoring the success of conservation work areas was carried out using a mixture of random and stratified placement of fixed 2 m x 2 m quadrats and surveys were initiated either before, or at the same time as the application of nurse crop seed. The time of the nurse crop seeding application was considered to be 'time zero' for the trajectory, being the main contributor to changes in cover. Other surveys, again involving fixed quadrats on bare peat patches, were conducted on areas that were excluded from any type of treatment, the 'control' sites, in order to provide a visual comparison and a justification that no statistical trajectory was found in these sites. A third category involved surveys using fixed quadrats on so-called 'intact reference' sites which were placed on areas of remnant vegetation and which may have experienced varying degrees of treatment. Details are provided in Annex 1.

2.1 Replacement of bare peat with vegetation

The cover of bare peat and vegetation decreased and increased, respectively, in a curvilinear relationship with time, in both cases the initial constant rate decelerating towards an equilibrium phase after about five growing seasons (Fig. 1, left).

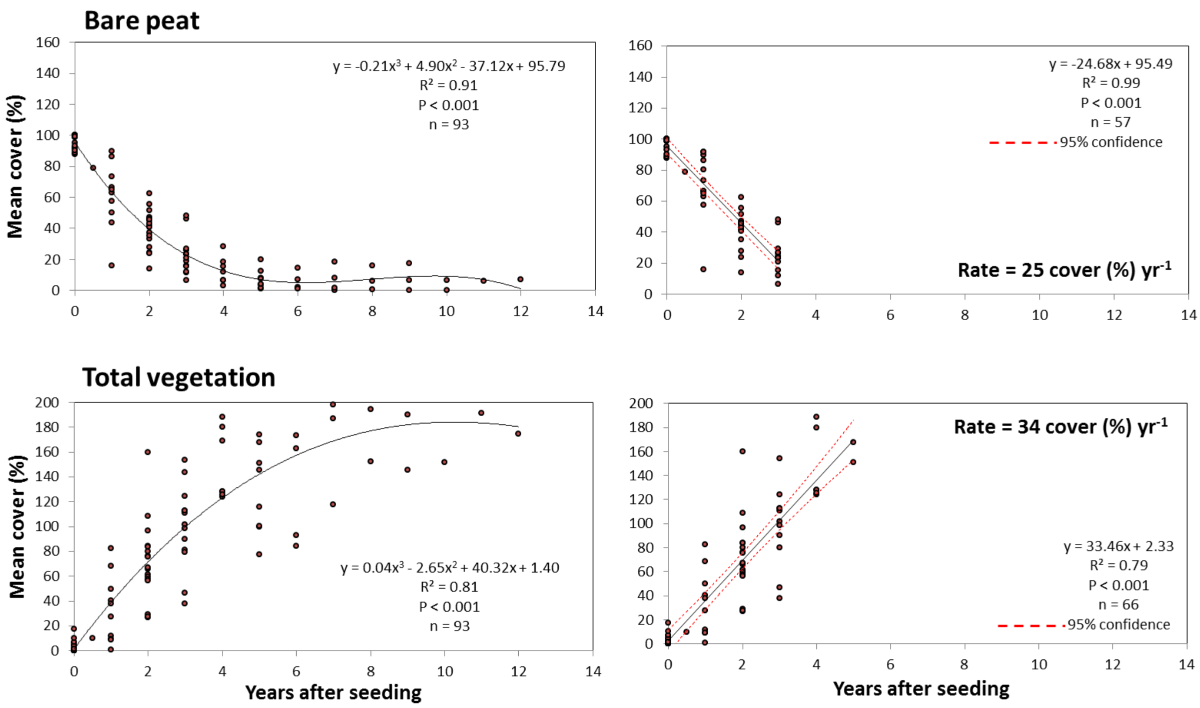

Fig. 1. Relationships between time and cover of bare peat (top), vegetation (bottom)
Curvilinear relationships (left) are described by quadratic or cubic functions of time. Linear relationships (right) are derived, where necessary, by the sequential removal of equilibrium values.
Regression coefficients (R^2), p-values (P) and number of replicates (n) are noted. For linear relationships only, Confidence limits (95%, CL) are also given; Cover is expressed as a mean percentage per 4 m^2 quadrat.

Statistically significant linear relationships derived from the above were achieved by sequentially removing data from the equilibrium phase of the dataset until no further changes in linear slope were found. The slope of the linear trajectories (Fig. 1, right), suggested that with starting values between 95 and 100% bare peat cover and between 0 and 5% vegetative cover, the predicted rate of change was approximately 25 (negative) and 34 (positive) cover percentage points per growing season, respectively.

2.2 Species dominance

Averaging over the spectrum of different sites with different survey durations, species cover was mainly dominated by grasses, both *acrocarpous* and *pleurocarpous* mosses and *Calluna vulgaris*. There was some representation by *E. vaginatum* and *E. angustifolium* too (Table 1).

Table 1. Average cover of species/groups

Species/Group	**Average cover (%)**
Grasses	31
Acrocarpous mosses	20
Pleurocarpous mosses	17
Calluna vulgaris	12
Eriophorum vaginatum	7
Eriophorum angustifolium	6
Vaccinium myrtillus	3
Empetrum nigrum	1
Rubus chamaemorus	0

The order of Species/Groups is defined by relative cover (%)
Grasses were dominated by *Deschampsia flexuosa; Calluna vulgaris* was the dominant dwarf shrub

In terms of trajectory of species, there was an early dominance of grasses, overtaken in time, or at least rivalled, by that of mosses, first pleurocarpous and then acrocarpous in habit (Fig. 2, left). There was also a relatively slow, consistent and growing dominance of *Calluna vulgaris*. Although the number of sites contributing to the data (and thus confidence in the data as an indication of general patterns) declined substantially with increasing age, and only one site had been restored 11 and 12 years previously (Fig. 2, right), nevertheless the pattern of early grass dominance and growing dominance by *Calluna* were common patterns amongst the individual sites and areas making up the trajectory in Fig. 2 (see Annex 1).

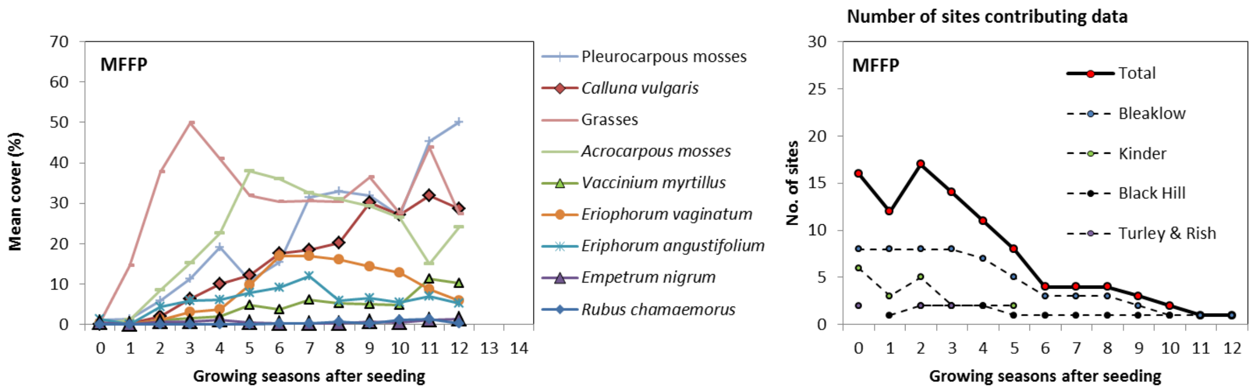

Fig. 2. Relationships between time and dominant groups/species (left), number of sites (right)
Relationships are described by direct line-plots, summarised over all sites and areas. Grasses were defined as belonging to the Gramineae, excluding the cotton grasses. The order of groups/types in the legend reflects dominance in the most recent year of data acquisition (left). The number of sites available for contributing data declined with time (right).

2.3 Control (bare peat) and reference (intact) areas

Restoration work was excluded from control sites. Reference sites were also surveyed, with quadrats positioned on remnant or 'intact' patches of vegetative cover. However, in some case, these latter sites may have received all or part of the re-vegetation treatments that were aimed at the adjacent bare peat areas. These control and reference sites were set up within the geographical areas of Kinder Scout, Bleaklow and Turley Holes & Rishworth (only reference type in the latter area) and data for key variables are presented as a summary of all areas (Fig. 3).

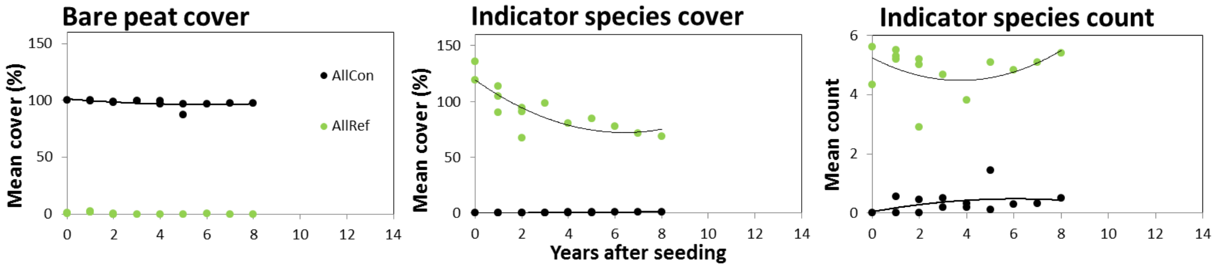

Fig. 3. Relationships between time and key variables in control/reference sites
Data are presented as a mean of all sites. AllCon = all bare peat control sites; AllRef = intact reference sites. Trajectories are presented as quadratic best-fit lines.

Data summarised over all of these sites/areas showed that bare peat cover remained relatively high in the control sites and approximately zero in the reference sites (Fig. 3, left). Similarly, the cover of indicator species remained approximately zero in the control sites, while appearing to decline from 120% to about 70% in the reference sites (Fig. 3, middle). Counts of indicator species remained negligible in the control sites, and the appearance of an increase over time was not significant. Counts of indicator species remained relatively high in the reference sites (Fig. 3, right).

Variations in indicator species cover/number in the reference sites are likely to be due to evolving interspecific competition pressures arising from the burgeoning cover of grasses and heather originating from the seed treatment. It is also likely that treatments of fertiliser and lime may have disrupted competitive balance within existing communities.

2.4 Favourable Condition

Favourable condition status requires that three key measures of cover (bare peat and indicator species) and number of indicator species fulfil certain minimum standards within a framework known as Common Standard Monitoring (CSM). The CSM 'targets' for these measures, or 'attributes' must fulfil two thresholds: one that is specific for the attribute, e.g. a minimum 'target' of 6 indicator species; and one that is general for all attributes, requiring that the individual targets should be met in over 90% of survey quadrat samples – usually 20 per survey. This study considers three key attributes targets – (i) less than 10% bare peat cover, (ii) at least 50% cover consisting of at least three indicator species and (iii) presence of at least six indicator species.

2.4.1 Key attribute 1: Bare peat cover less than 10%

The proportion of quadrats with bare peat cover less than 10% increased over time (Fig. 4, left), described by a significant quadratic function. The increase was initially steep, slowing to an equilibrium phase after about 5 growing seasons (Fig. 4, left).

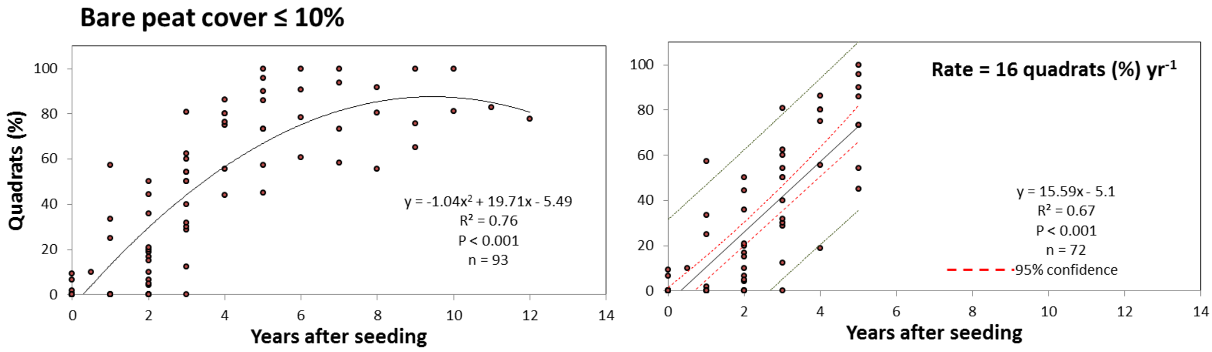

Fig. 4. Relationships between time and the proportion of quadrats with less than 10% bare peat cover
Details and explanations as in Fig. 1

Simple linear relationships were derived by removing data points until further changes to the slope were minimised (Fig. 4, right). The slope of the line suggested that with starting values of approximately 0 %, the predicted rate of increase was 16 percentage points per growing season, over five growing seasons

2.4.2 Key attribute 2: At least 50% cover composed of at least three indicator species

The proportion of quadrats with at least 50% of the vegetation cover composed of at least three indicator species increased significantly in a curvilinear relationship with time (Fig. 5, left).

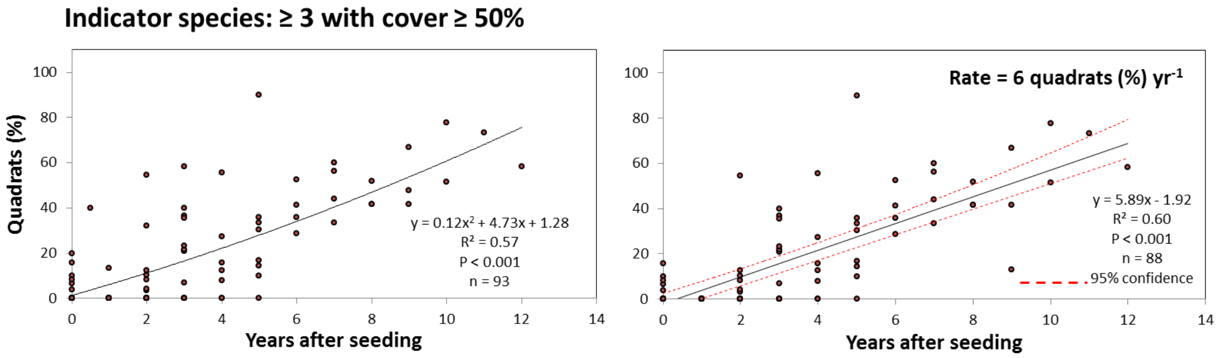

Fig. 5. Relationships between time and the proportion of quadrats with at least 50% cover composed of at least three indicator species (bare peat plots)
Details and explanations as in Fig. 1

Simple linear relationships were derived without the need for removing datapoints (Fig. 5, right) and the slope of the line predicted an increase of 6 percentage points per growing season over at least 12 growing seasons.

2.4.3 Key attribute 3: At least six indicator species

The proportion of quadrats with at least six indicator species appeared to increase relatively slowly over time (Fig. 6, top and middle left). A high-reading outlying data point (Fig. 6, top left) can be attributed to quadrat location and the introduction of *Sphagnum* plugs at this time (see Annex 1).

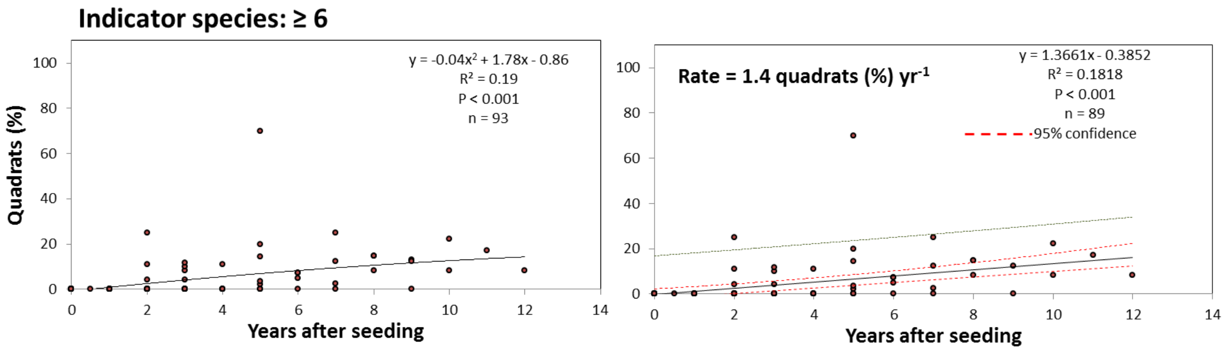

Fig. 6. Relationships between time and the proportion of quadrats with at least six indicator species (bare peat plots)
Details and explanations as in Fig. 1

Simple linear relationships were derived without the need for removing data points (Fig. 6, right). The resulting slope predicted a rate of increase of about 1.4 percentage points per growing season respectively, over at least twelve years.

3 WATER TABLE TRAJECTORIES (SUMMARISED FROM ANNEX 2)

3.1 Manual dipwell data

Due to high inter-annual variation of hydro climate and subsequent effects on water table depth, temporal changes of water table depth as a function of restoration activities was calculated as a relative difference to the water table depth in the bare peat control. Potential errors associated with this approach, i.e. erosion of the bare peat surface in the control sites, would tend to exaggerate values of depth to water table in the treatment sites – i.e. the approach is considered conservative.

Data from seventeen dipwell clusters situated within the four MFFP restoration areas were analysed to show temporal trends in water table height over a maximum period of 12 growing seasons post seeding. Fourteen of these clusters showed water tables rising towards the surface relative to control clusters. Individual rates of change for each cluster were derived from a trend line fitted through the annual data points – the average rate of change over all clusters suggested that water tables were rising to the peat surface at a rate of 24 mm per year.

This trend can be depicted as a linear trajectory (Fig. 7), where the Y axis was normalised so that the water table changes are relative to the pre-restoration condition, i.e. at the time of restoration the deviation is zero. For the ‘late stage’ restoration sites (Black Hill and Bleaklow), for which a complete data set was not available, the trend in water table change apparent during the later measured period was assumed to apply to the whole period of restoration in order to define a Y axis position for the points. The dotted lines on the plots linking the late stage data to the origin indicate this assumption.

There was some indication that longer running sites had higher average rates of change, but due to sample size, this conclusion is uncertain. Nevertheless, over all longer and shorter term sites, there was a strong indication of a relatively slow but consistent recovery, which has the potential to influence hydrological functioning.

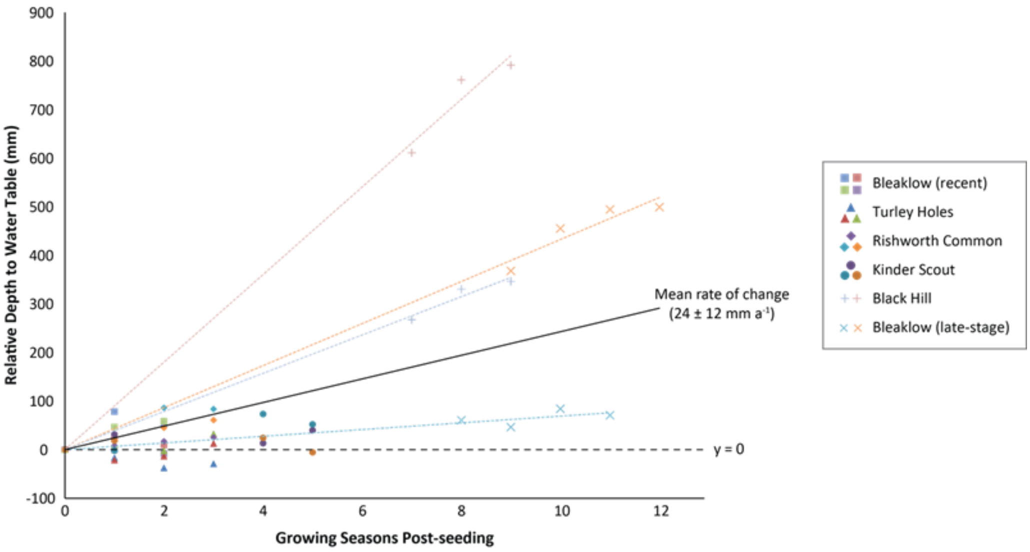

Fig. 7. Trajectories of water table change based on manual campaign data.
Depth to water table is relative to the bare peat control site. ‘Late stage’ data (Bleaklow and Black Hill) are plotted in Y axis positions based on extrapolation of the local trend to the origin (indicated by the dotted lines, see text).

3.2 Automated dipwell data

Automated dipwell data were derived from automatically logging sensors within the dipwells. Issues with low replication of automated dipwells and especially with calibration of these data mean that the absolute values of water table as calculated from automatic loggers are probably less secure than those derived from the manual data. However, there were also advantages associated with automatic data – in particular the conservative effect associated with erosion of the bare peat surface of the control sites for the manual data mentioned above is not applicable because measurement is relative to the dipwell base rather than the ground surface. Moreover, short term variations in water table recorded by the logging dipwells allowed a comparison of water table behaviour between sites. As for manual data, inter-annual variation in hydroclimate changes in water table was managed by assessing change relative to a control site. Lines of best fit were fitted through the data to assess trends over the period of observation.

Six out of eight sites showed water tables rising to the surface following the seeding treatment. Over all sites the average rate of change was 36.7 mm (but with a large variation). The overall rate of change is greater than that identified in the manual data which may relate to the fact that the manual data were conservative. These trends can be depicted as a linear trajectory (Fig. 8), with the same assumptions for the y-axis as detailed in section 3.1, above.

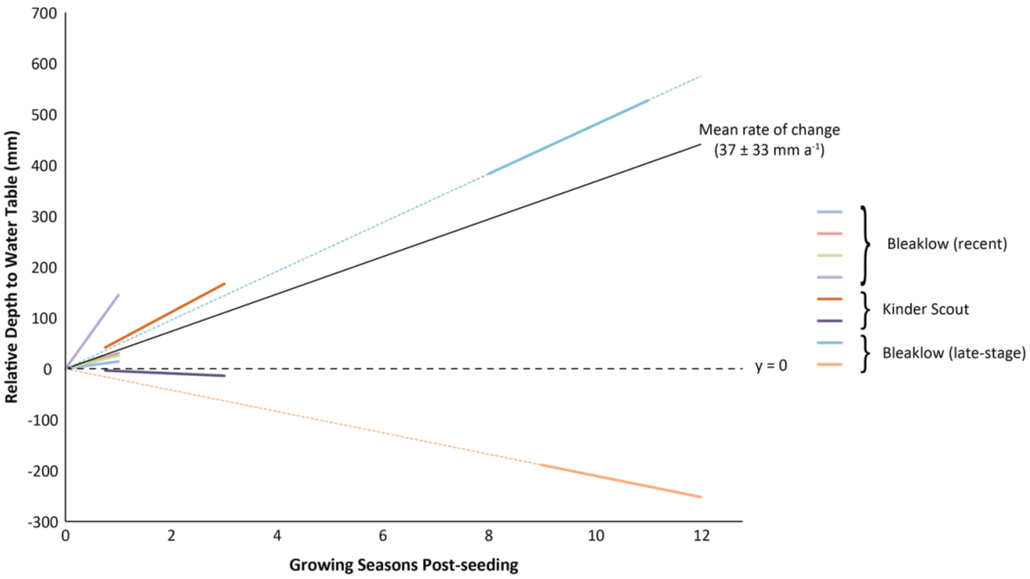

Fig. 8. Trajectories of water table change based on automatic continuous monitoring.
Depth to water table is relative to the bare peat control site. Solid lines indicate the trends derived from the continuous data or the period of monitoring. 'Late stage' data are plotted in Y axis positions based on extrapolation of the local trend to the origin (indicated by the dotted lines, see text).

3.3 Commentary on water table trajectories

The positive impacts of re-vegetation on water table, although relatively small on an annual basis, continued to accrue for periods in excess of 10 years.

Comparison of the trajectories from early and late stage restoration suggests that more rapid changes may be occurring 10 years after restoration than in the first few years. Possible mechanisms include vegetation succession leading to changes in surface character and infiltration capacity, and/or progressive recovery of peat structure and hydrological function. Longer term monitoring at recently restored sites is required to assess these issues more fully.

While the positive impact demonstrated here is evidence for hydrological recovery associated with re-vegetation, complete restoration of water table behaviour in heavily degraded systems will be constrained by long term changes to peatland topography, due to the influences of erosional gullying.

With these relatively small rates of annual change, longer term observations are required to provide increased confidence in these results by improving the signal to noise ratio in the data.

Ongoing monitoring of recently restored sites will provide confidence that the relatively faster changes associated with the late stage sites observed here were real and not a result of site to site difference in water table behaviour.

Future investigations into those sites showing negative dipwell trends have the potential to provide useful information relevant to the conservation process.

3.4 Relationship between vegetation cover and water table

Active blanket bogs are covered with vegetation which includes a relatively high percentage of *Sphagnum* mosses. The upper active layer of these systems (the 'acrotelm') controls exchanges of moisture with the atmosphere and has a relatively high hydraulic infiltration rate compared to the lower catotelm layer. These systems maintain the moisture level of peat above the water table at or near saturation even in dry periods so that even a small rain event will, relative to other non-peat systems, lead to rapid rises in water table and rapid generation of saturation-excess overland flow. The lowering of water tables to levels below the acrotelm in summer dry periods leads to sharp falls in throughflow discharge which cuts off base flow and leads to a characteristically flashy system.

On blanket bogs devoid of vegetation, the absence of an active acrotelm slows infiltration rates, promotes radiative heating and increased rates of evaporation, drying the peat and lowering water tables. Deep erosional gullying is a major additional factor responsible for lowered water tables.

Recent results from the Making Space for Water project (Pilkington et al., 2015) have provided evidence that re-vegetation of bare peat was associated with raised water tables and increased generation of overland flow, the former potentially causing the latter. From the more recent analysis of a longer temporal dataset, there is now good evidence that the rise in water tables is linear, persisting over at least 10 years since the start of the restoration activities (Fig. 9 , left and middle).

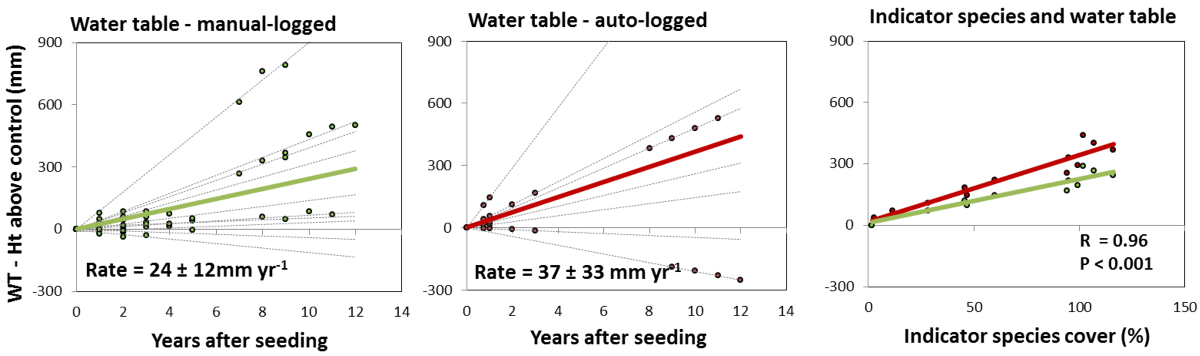

Fig. 9. Relationships between time, water table depth and the cover of indicator species
Water table (WT) depth is expressed as depth relative to depth in a non-vegetated control

Trajectories of key vegetation parameters (with linear increases of a similar longevity, persisting over at least 10 years), included the cover of blanket bog indicator species (Fig. 9, right). The involvement of indicator species rather than general vegetation may be important for two reasons: the development of a less decomposable litter layer (acrotelm) resulting from higher concentrations of phenols (and lower decomposition rates) in the tissues of non-graminoid moorland plants (Pilkington et al, 2005); and the more conservative evapotranspiration rates associated with non-graminoid moorland plants (Schouwenaars, 1995)

4 WATER FLOW TRAJECTORIES (SUMMARISED FROM ANNEX 3)

Analysis of six years of stormflow data at restored peatland sites in the southern Pennines suggested that lag times increased, peak discharge decreased, and storm hydrographs became less flashy following restoration (Fig. 10, left and middle). The effects are best characterised as a step-change occurring in the year immediately following restoration. The findings support the hypothesis that changes in storm behaviour are driven by reduced overland flow velocities resulting from increased surface roughness. Future monitoring of the sites is recommended following additional changes to hillslope surface roughness (i.e. the establishment of sphagnum cover in site N). A minimum period of three years of monitoring is recommended to assess such changes to account for inter annual variability, but this does not need to be continuous with the existing data.

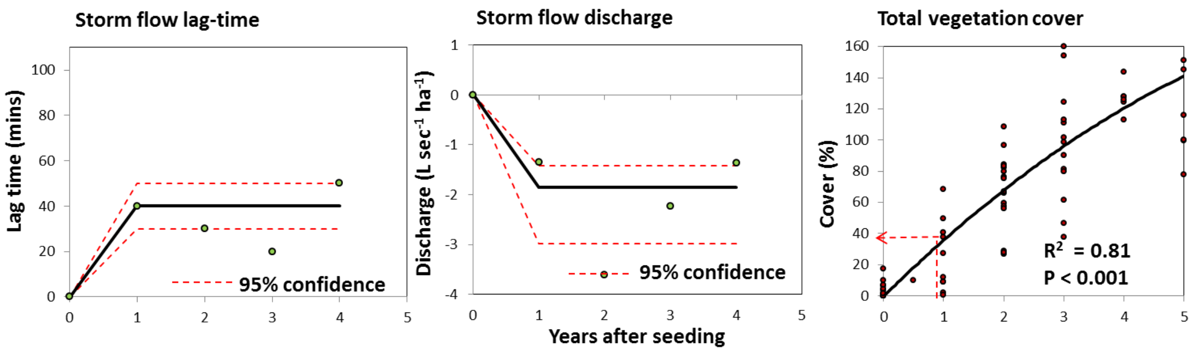

Fig. 10. Relationships between time, key hydrograph metrics during storms (lag time and peak discharge) and total vegetation cover

The hypothesis that changes in storm flow behavior are driven by reduced overland flow velocities resulting from increased surface roughness can be further substantiated from vegetation surveys which suggest that the most rapid rise in vegetative cover occurs in the first year after seeding (Fig. 10, right).

5 WATER QUALITY TRAJECTORIES (SUMMARISED FROM ANNEX 4)

Water samples were collected by Moors for the Future Partnership (MFFP) from stabilised bare peat blanket bog sites in the Dark Peak and South Pennines. The samples were filtered at 0.45 microns prior to spectrophotometric absorbance analysis at wavelengths of 254, 400, 465 and 665nm. The samples were then sent to Scientific Analysis Laboratories Ltd. (Manchester) for analysis of water colour, pH and absorbance as well as DOC and a range of metals.

The results showed that treatment works (gully-blocking and application of lime, seed and NPK fertiliser) did not have significant impacts on water quality in the short to medium term.

However, elevated concentrations of Calcium (Ca), a major component of the lime treatment, was still present in headwater streams some 18 months after the final dose of three annual applications of lime starting at the time of the seeding. This was accompanied by increased pH levels.

Annual mean concentrations of Dissolved Organic Carbon (DOC) did not change as a result of treatment and changes to the composition of DOC were not clearly evident.

Longer-term monitoring is required to create statistically significant trajectories of change as a result of restoration works, because of the observed and potential confounding effects of the treatments and insufficient data are available from after the cessation of the treatments. Post-treatment data extended to a maximum of three years following the cessation of treatment (and to a maximum of

18 months for some determinands); this is therefore the current limit to the timeframe of the trajectories of change it is possible to create.

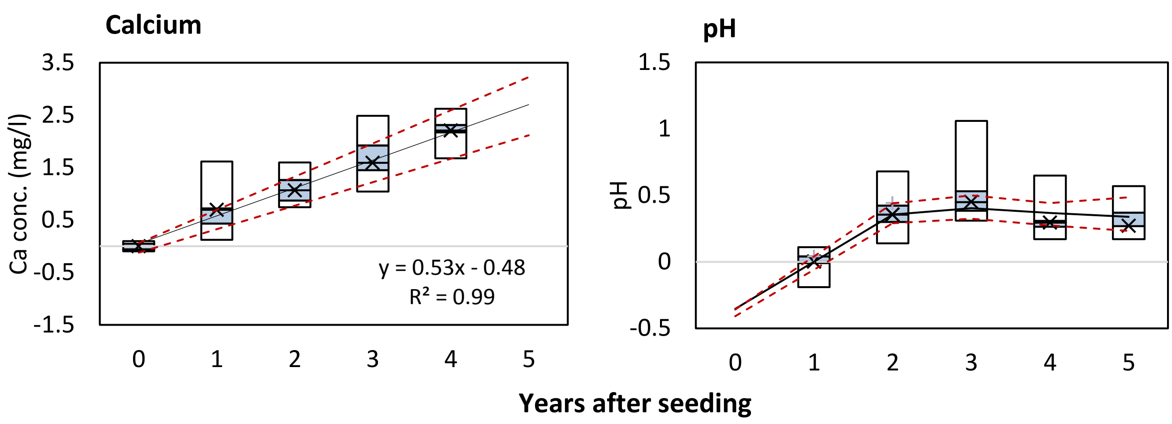

Fig. 11. Relationship between time and: Calcium concentration (left); pH (right)

Values are given relative to a bare peat control site
X = annual median; = line of best fit (annual median); = 95% confidence interval about the annual median where appropriate; = interquartile range; = range

6 SEDIMENT ACCUMULATION TRAJECTORIES (SUMMARISED FROM ANNEX 5)

Dense networks of deeply incised gullies are the result of severe erosion in degraded blanket bog sites in the South Pennines. These channels create highly efficient drainage networks for the transport of runoff in storm events, and eroded sediment from the peat surface. Gully-blocking has been undertaken at the landscape scale, with the intention of slowing the velocity of storm runoff, raising water tables in the surrounding peat, and trapping sediment.

This report assesses the efficacy of gully-blocking, in relation to trapping sediment, thereby reducing carbon export from the peatlands. Data were collected by Moors for the Future Partnership (MFFP) by monitoring sediment depth change as a result of installing gully blocks using a range of materials. Analysis of these data shows that all types of gully blocks monitored successfully trap sediment during the first two years after installation. Insufficient data were available to draw reliable conclusions as to the relative successes of each type of gully block. Long-term data were not available, and are required in order to assess the scale and longevity of the impact of gully blocking on sediment accumulation.

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