

Moor Water

*Monitoring the impact of restoration of degraded blanket bog sites on
Dissolved Organic Carbon (DOC) in streamflow at headwater catchments*

2025

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I. Summary

- The Moor Water project built on work of MoorLIFE 2020 project and Making Space for Water project, in monitoring Dissolved Organic Carbon (DOC) in streamflow from experimental plots at headwater mini-catchments on degraded peatland.
- Samples were taken from the outflow of V-notch weirs at restoration sites with a bare peat starting state, and those dominated by common heather (*Calluna vulgaris*) and hare’s-tail cotton-grass (*Eriophorum vaginatum*).
- At the ‘bare peat’ sites on Kinder Scout, the project added a further 3 years of data to the 10 years collected previously.
- At the ‘species-dominated’ sites, the project added a further 3 years of data to the 3 – 4 years collected previously.
- During the Moor Water monitoring period, DOC concentration was modelled using absorbance at different wavelengths, and DOC instantaneous load was then calculated using stream discharge data.
- No clear change was detected in DOC load at the bare peat sites on Kinder Scout.
- A possible decrease in relative DOC concentration was found at N in 2024 – the revegetated, gully-blocked and *Sphagnum*-planted site on Kinder Scout. This requires further monitoring and investigation to verify.
- No clear change was detected in DOC concentration or load at the species-dominated sites.
- Increased sampling frequency with direct DOC measurements, and/or the use of continuous monitoring (storm sampling) is recommended.

2. Introduction

Historic degradation of peatlands across the South Pennines led to large areas of bare peat, severe erosion, lowering of water tables and dominance of single vegetation species. This degradation, as well as restoration methods used on these peatlands, may have implications for water chemistry – including concentration of Dissolved Organic Carbon (DOC) in streamflow discharged from degraded headwater catchments. Work to date on the sites monitored in this project was discussed in detail in the final report of the MoorLIFE 2020 project (Moors for the Future Partnership, 2022).

This report for the Moor Water project builds on the work carried out for the MoorLIFE 2020 project (and, preceding that, the Making Space for Water project) and should be regarded as a partial update to the Water Chemistry chapter (6) of that document. As such, parts of the following introductory section are taken from that the MoorLIFE 2020 report and updated where necessary.

2.1. Peatland degradation

As discussed in Spencer and Evans (2016), a combination of human and natural influences has led to severe degradation of peatlands in the uplands of the South Pennines and Peak District (Tallis, 1998). Widespread erosion caused loss of vegetation cover and generated large expanses of bare peat and deeply incised gully networks. Subsequent drying of the peat mass restricted the possibility of vegetation recovery and increased rates of erosion. This contributes to increased concentrations of dissolved and particulate organic carbon and other nutrients or pollutants in the waters draining from these headwater catchments (Bussell *et al.*, 2010), with financial implications for utility companies removing these substances from drinking water supplies (Wallage *et al.*, 2006), as well as environmental impacts on the global carbon cycle including fluvial conversions of dissolved and particulate organic carbon (DOC and POC) to carbon dioxide (CO₂) (Evans *et al.*, 2013).

During and since the Industrial Revolution, rates of deposition of industrial pollutants including sulphur and nitrogen have been high. While nitrogen stimulates Net Primary Productivity (NPP) in plants, the acidification of the peat surface by sulphur has historically negated this effect. However, since the 1970s, rates of sulphur deposition have declined, due to efforts to reduce human-driven atmospheric pollution. With the resulting increase in soil pH, combined with possible changes in climate, the historically deposited nitrogen store is being activated, causing an increase in NPP, and therefore DOC (Monteith *et al.*, 2015).

2.1.1. Dissolved organic carbon (DOC)

DOC is a complex group of organic carbon-containing compounds, including aromatic, phenol and carboxyl groups. These compounds contain other elements – usually hydrogen, oxygen and nitrogen. The composition (elemental and structural) varies based on site characteristics (e.g. soil and vegetation cover, land management, peat depth), weather, climate and location. DOC in peatland waters is derived from humic substances, and contains humic and fulvic acids.

2.2. Peatland Restoration and potential impacts on water quality

Peatland stabilisation has been undertaken at the landscape scale on extensive areas of bare and eroding peat in the South Pennines, as detailed in Buckler *et al.* (2013). Work has focused on:

- Stabilising the large contiguous areas of bare and eroding peat through establishing and subsequently diversifying vegetation cover through the application of heather brash, amenity/local grass and heather seeds, granulated lime and fertiliser (three annual summer applications by helicopter-suspended hopper, see Table 1), *Sphagnum* mosses and other moorland species plug plants.
- Rewetting the peat mass and slowing the flow (and therefore reducing the erosional force) of storm-water from the headwaters to the river networks by blocking gullies and grips using stone, timber, plastic or peat dams.
- Planting *Sphagnum* mosses to encourage carbon sequestration, enhance the temporary water storage capacity of the vegetation canopy and increase hillslope surface roughness to reduce overland flow velocities.
- Improving footpaths to reduce erosion due to high footfall on popular walking routes.

Table 1: Typical lime and fertiliser components and application rates used by MFFP (Pilkington, 2015)

	Granulated lime components	Application rate	Granulated fertiliser components	Application rate
Year 1	98% Ca, 0.5% Mg, 1% Si ₂	1000 kg/ha	40 N : 120 P ₂ O ₅ : 60 K ₂ O	361 kg/ha
Year 2	98% Ca, 0.5% Mg, 1% Si ₂	1000 kg/ha	40 N : 60 P ₂ O ₅ : 60 K ₂ O	278 kg/ha
Year 3	98% Ca, 0.5% Mg, 1% Si ₂	1000 kg/ha	40 N : 60 P ₂ O ₅ : 60 K ₂ O	278 kg/ha

Granulated lime and fertiliser are applied to bare peat treatment sites to create soil conditions in which the nurse crop species can survive. Pre-treatment soil conditions are characterised by very low pH (2.5–3) and nutrient levels (Buckler *et al.*, 2013). Caporn *et al.* (2007) found that lime and fertiliser are required in combination with each other to promote successful plant establishment and development at degraded bare peat sites. The calcium and magnesium components of lime were in the form of calcium carbonate and magnesium carbonate respectively.

These works may have a range of implications for water quality. Whilst some studies have suggested restoration may lead to short and/or longer-term reductions in DOC and water colour (Evans *et al.*, 2015, Wallage *et al.*, 2006), others report increases (Strack *et al.*, 2011). Additionally, some studies suggest that DOC production is increasing in UK upland catchments, regardless of specific restoration works (Monteith *et al.*, 2015).

The application of lime and fertiliser has been shown to result in short-term increases of pH and fluvial concentrations of the components of these treatment products, but the longer-term impacts, and the residency times of these components in the headwater streams are, as yet, unclear. The increase in pH could lead to interactions with metal pollutants stored in the peat mass and the organic materials that produce DOC (Rothwell *et al.*, 2007; Stimson, 2015).

This study extends datasets previously reported in Spencer and Evans (2016) and then Evans *et al.* (2022). The current study adds an additional four years of data, providing important new evidence of the impacts on water chemistry of bare peat restoration techniques.

In addition to presenting extended bare peat restoration data, this study examines the impacts of *Sphagnum* introduction on water quality in areas dominated by a single species: *Calluna vulgaris* and *Eriophorum vaginatum*. *Sphagnum* species are important for peatland carbon storage, and introducing *Sphagnum* to areas of land dominated by vascular plants can increase carbon storage. However, studies that demonstrate significant change in surface water quality as a result of *Sphagnum* planting are scarce (Ritson *et al.*, 2017), despite several studies showing that the type of vegetation on a peatland can influence the production and release of DOC (Armstrong *et al.*, 2012).

The water chemistry at sites dominated by the species listed above, were monitored over a four-year period for the MoorLIFE 2020 project, in order to examine the impact of planting *Sphagnum* moss plugs at varying densities across mini-catchments. This current study adds an additional three years of data.

3. Location of the project area

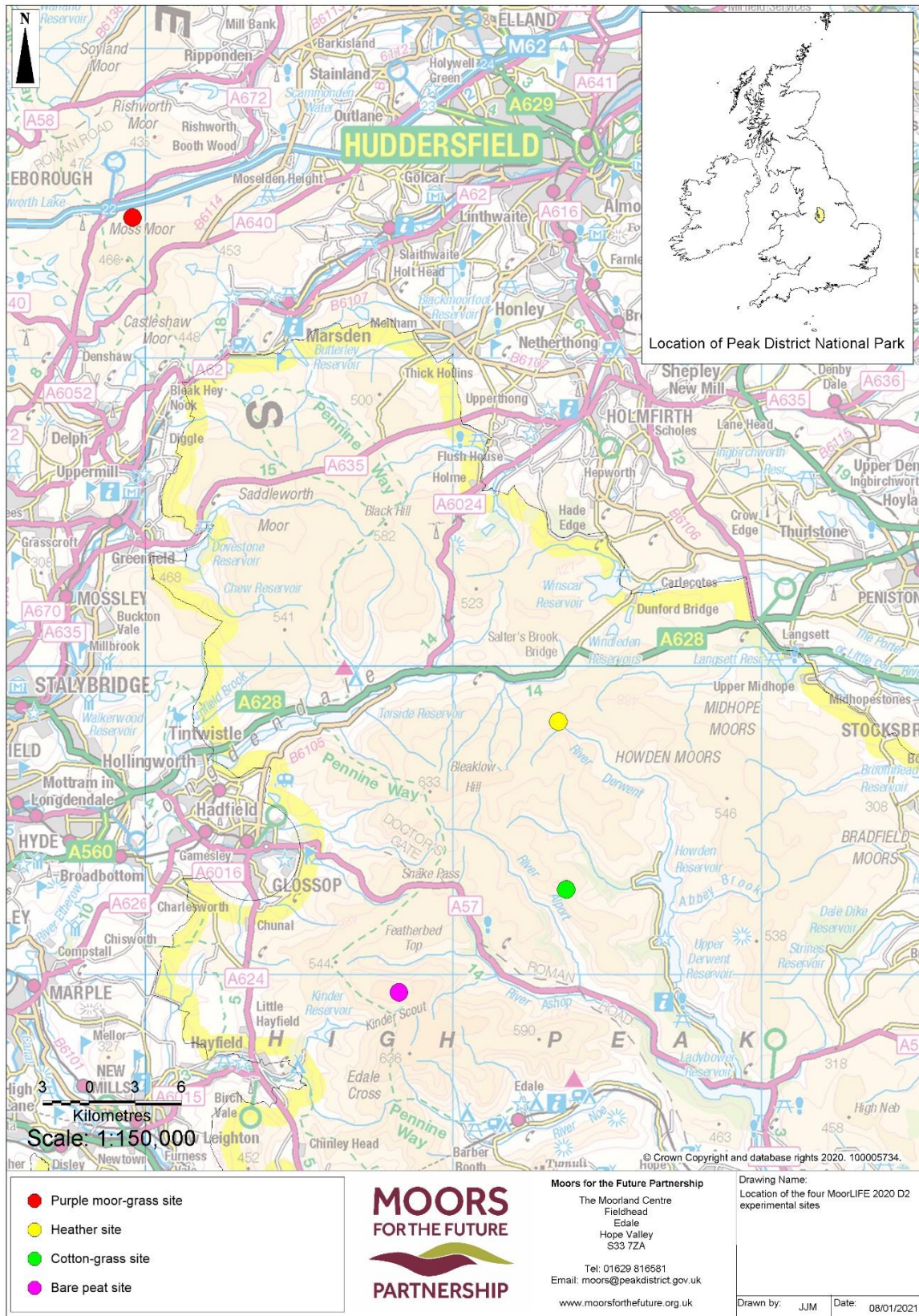


Figure 1. Locations of the four experimental sites within the ML2020 D2 project area. For the Moor Water project, water quality monitoring continued at all sites aside from the Purple moor-grass site at Moss Moor.

3.1. Bare peat sites

The Moor Water Bare Peat (formerly MoorLIFE 2020 / Making Space for Water) project area is situated on the north Edge of the Kinder Scout plateau within the Peak District National Park and between Manchester and Sheffield (Figure 2 **Error! Reference source not found.** **Error! Reference source not found.**). Much of the the Peak District National Park is above 300 m, with the highest point on Kinder Scout at 636 m. The area is characterized by hills and gritstone escarpments (“edges”). The project area has approximate dimensions of 2000 m x 400 m, an area of approx. 84 ha and an average height of 600 m above sea level.

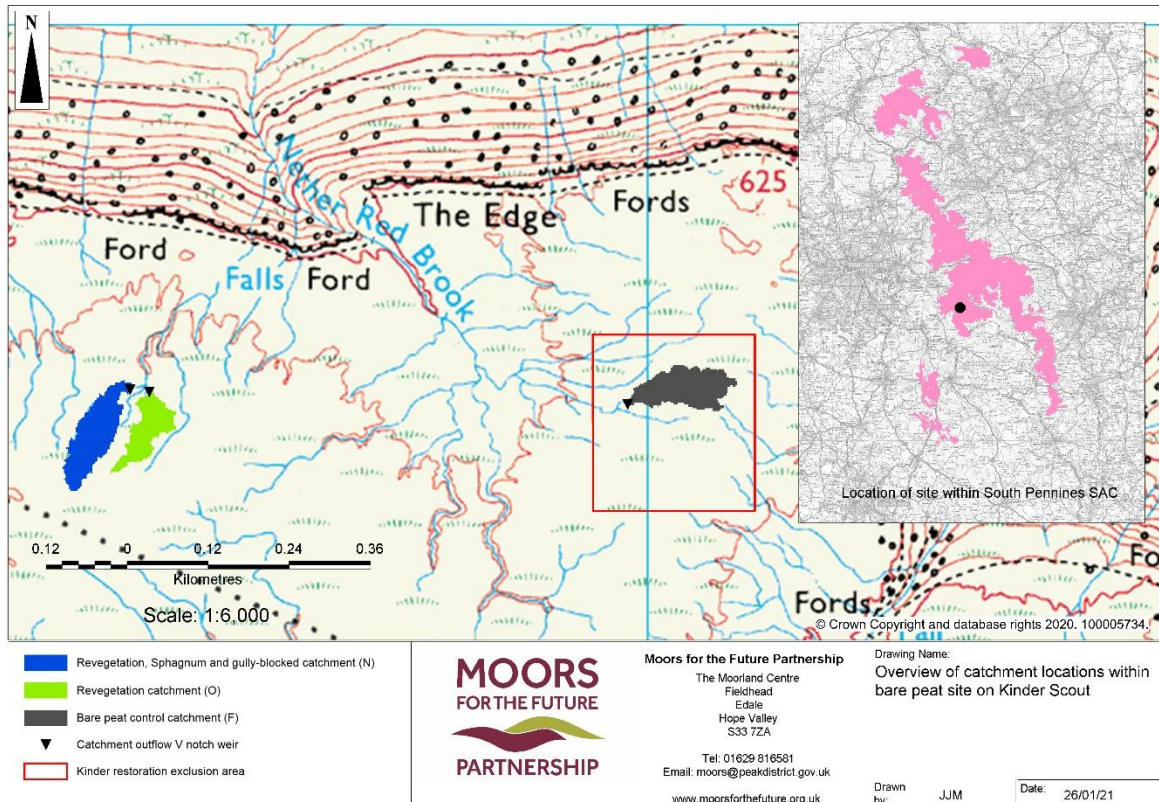


Figure 2. Bare peat project area

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



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

3.2. Species-dominated sites

The Moor Water (formerly MoorLIFE 2020) ‘species-dominated’ sites are situated in three locations. The *Calluna* and *Eriophorum* sites (the two where water quality monitoring continued for this project) are both within the Peak District National Park, and the South Pennines SAC (see **Error! Reference source not found.**).

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

3.2.1. *Calluna*-dominated area

The project area is situated at Swain’s Head on Howden Moor, South Yorkshire within the upper catchment of the River Derwent (Figure 4**Error! Reference source not found.**). It is approximately 10 kilometres north north east of the Bare Peat site. The site is owned by the National Trust and is within the boundary of the Peak District National Park. It is located less than 100 m from the county boundary with Derbyshire.

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

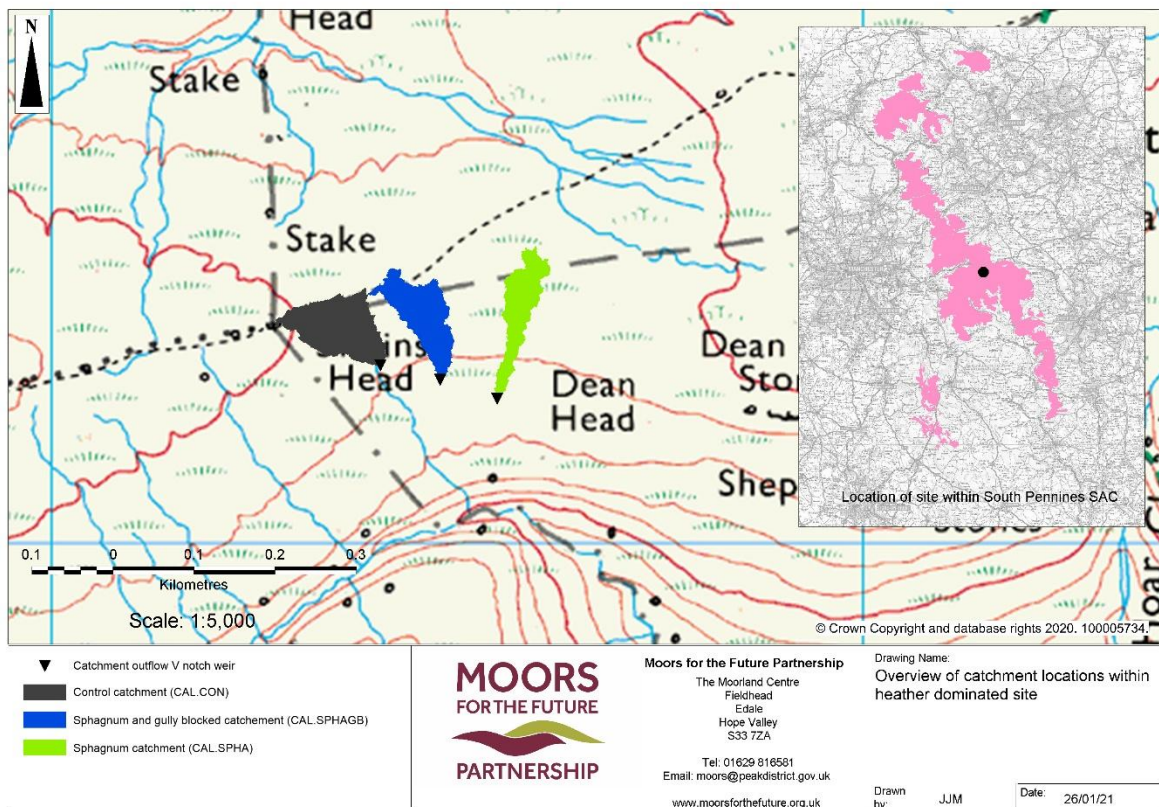


Figure 4. Overview of the *Calluna*-dominated site

3.2.2. *Eriophorum*-dominated area

The project area is situated at Birchinlee Pastures on Alport Moor, Derbyshire – approximately six kilometres northeast of the Bare Peat site (Figure 5). The site is owned by the National Trust and is within the boundary of the Peak District National Park. The two experimental mini-catchments within the area are situated along a watershed and drain into different river basins. The control mini-catchment drains to the west into the Westend catchment – a tributary of the River Derwent. The treatment mini-catchment inoculated with *Sphagnum* drains into the Alport catchment to the east.

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

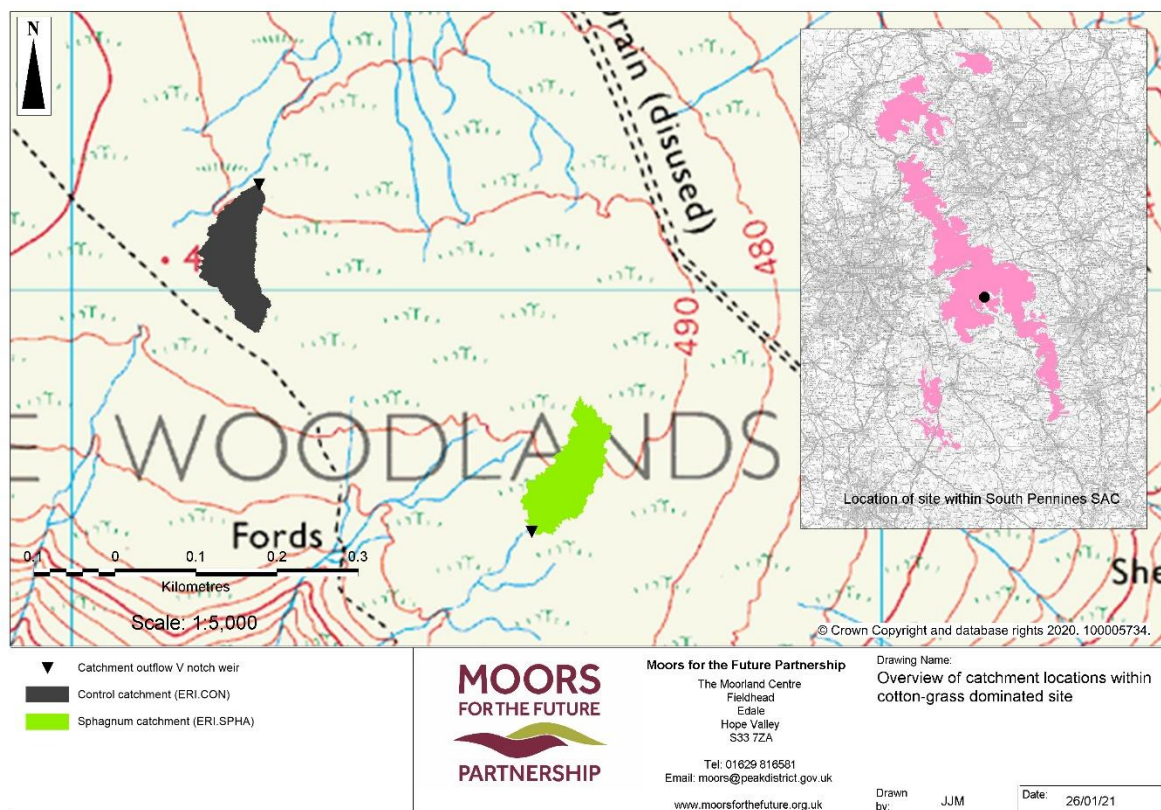


Figure 5. Overview of *Eriophorum*-dominated site

4. Treatment

Table 2 below contains a summary of restoration interventions made at each site. Full details of each can be found in section 4 of the introductory annex of the MoorLIFE 2020 final report (Margetts, J.J., Pilkington, M.G. and Spencer T., 2022).

Table 2. Restoration methods used at all sites

Restoration process	Bare Peat sites				Calluna site			Eriophorum site	
	F	P	O	N	Con	Spha	SphaGB	Con	Spha
Grazing exclusion	2013	-	2013	2013	-	-	-	-	-
Gully blocking	-	-	-	2011	-	-	2019	-	-
Heather brash	-	-	2011	2011	-	-	-	-	-
Geo-jute	-	-	2011	2011	-	-	-	-	-
Seeding: amenity grasses and moorland species	-	-	2011	2011	-	-	-	-	-
Lime + fertiliser	-	-	2011 2012 2013	2011 2012 2013	-	-	-	-	-
<i>Sphagnum</i> planting	-	-	-	2015 2018	-	2019	2019	-	2019

5. Methodology

5.1. Data collection

5.1.1. Bare peat sites

Water samples were collected at field lab sites F (bare peat control), O (revegetated), N (revegetated, gully-blocked and *Sphagnum*-planted) and P (intact reference) from 2011–2020. From 2021–2024 samples were collected from F, O and N, but not P. All samples were collected in 30 ml plastic sampling tubes from stream discharge flowing through the v-notch weir at each mini-catchment. All sample tubes were triple-rinsed in stream water before sampling. If there was no flow (during dry periods), samples were not collected. All samples were then stored in an opaque bag while on site and refrigerated until they were analysed in the laboratory.

Samples were collected during routine visits to the field labs. Frequency of sampling visits varied (from fortnightly to monthly or less frequently) through the monitoring period. Samples were collected in a range of flow conditions but none from high-flow events; the majority were from baseflow.

5.1.2. Species-dominated sites

On each site visit (approximately fortnightly) between 2018 and 2021, water samples were collected from each weir; from stream discharge flowing through the v-notch at each mini-catchment. All samples were collected in pre-rinsed 50 ml plastic tubes. If there was no flow (during dry periods), samples were not collected. All samples were then stored in an opaque bag while on site and refrigerated until they were analysed in the laboratory.

From 2022 to 2024 samples were collected on each visit (approximately every 6 weeks, or less frequently in 2022). Again, samples were collected in pre-rinsed 50 ml plastic tubes. All samples

were then stored in an opaque bag while on site and filtered and refrigerated until they were analysed in the laboratory.

5.2. Water chemistry analysis

5.2.1. Bare peat sites

At the laboratory, samples were filtered at 0.45 microns. From 2011–2014, samples were analysed colorimetrically using a Hach spectrophotometer. Absorbance was measured at 254 nm, 400 nm, 465 nm and 665 nm; absorbance at 400 nm was used as a proxy for DOC in 2011. From 2012–2020 DOC was also measured directly, as non-purgeable organic carbon (NPOC) via UV-persulphate oxidation on a Shimadzu TOC analyser. Water chemistry was analysed by ICP-OES and Ion chromatography to provide contextual data. From 2021 onwards, DOC was no longer measured directly, and absorbance was measured at eight wavelengths (665, 470, 465, 436, 400, 360, 265 and 254 nm) in the Moors for the Future Partnership laboratory using a Jenway spectrophotometer. Periodically, a sub-set of samples were sent to the University of Leeds for quality control.

5.2.2. Species-dominated sites

At the Moors for the Future Partnership laboratory, samples were filtered as soon as possible after collection, and refrigerated before being sent to the University of Leeds. From 2018–2021, the absorbance at eight wavelengths (665, 470, 465, 436, 400, 360, 265 and 254 nm) was measured by UV-Vis spectrophotometry at the University of Leeds. From 2022 onwards, absorbance was measured at eight wavelengths (665, 470, 465, 436, 400, 360, 265 and 254 nm) in the Moors for the Future Partnership laboratory using a Jenway spectrophotometer. Periodically, a sub-set of samples were sent to the University of Leeds for quality control.

5.3. Data processing and analysis

5.3.1. Bare peat sites

2011 data were converted from absorbance to DOC, primarily using Abs_{400} data. Data from all four wavelengths were tested using the Kruskal-Wallis independent samples test for treatment effect to see whether the DOC: Absorbance relationship was affected by treatment (application of lime may affect pH which may, in turn affect the type of DOC – and therefore the absorbance at different wavelengths – as well as the amount). Where a significant effect was noted, these wavelengths were excluded before a multiparameter model was fitted in cases where this significantly increased the fit above using 400nm alone. 2012 data onwards did not need processing in this way as they were from direct measurements. The different method used in the pre-treatment year could be a possible source of error in the analysis. Subsequent modelling of DOC between 2021 and 2024 was based the relationship between measured DOC and Abs_{400} found between 2011 and 2020.

Preliminary analysis of the 2011–2020 DOC data suggested no relative change in DOC concentration between control (F) and treatment (O, N) sites but that discharge had. Therefore, it was possible that DOC load may have changed – if it were static, an increase in discharge would cause a dilution in concentration. DOC instantaneous load (mg/s) was calculated by multiplying daily mean discharge from the day of sampling (l/s) by DOC concentration (mg/l).

DOC instantaneous load data from field labs F and O, and F and N were compared using a paired BACI design. This reduced the available dataset due to the requirement to have both DOC and discharge data from both sites to be compared for any one datapoint. However, by comparing both

treatment sites to control, but not to each other, this allowed for more datapoints to be used than in previous analysis. Initial applications of lime started in autumn 2011 so data were only available for the baseline year from January to July. To avoid bias in post-treatment data, August–December data were excluded from all years, further reducing the size of the dataset.

Where data were available, relative DOC instantaneous load and concentration (treatment-control) was calculated to isolate any effects on DOC of the treatment itself. Differences between years were tested using Kruskal-Wallis independent samples test and Dunn-Bonferroni post-hoc tests.

5.3.2. Species-dominated sites

Before intervention, the DOC concentration of the water samples was directly measured in order to calculate a relationship between the absorbance and carbon concentration (Equation 1; Equation 2 **Error! Reference source not found.**). The DOC concentration was measured on samples collected in September 2019 in order to check the relationship between absorbance and carbon concentration. For consistency, same equations were as above were used to model DOC concentration for data collected during the 2022–2024 period.

DOC concentration values (mg/l) were derived for all samples, and as at the bare peat sites, DOC instantaneous load (mg/s) was calculated by multiplying daily mean discharge from the day of sampling (l/s) by DOC concentration (mg/l). For consistency the additional data were grouped by year, running from April to end March, as was the case for the previous MoorLIFE 2020 analysis. DOC instantaneous load data from field labs Eri.Con and Eri.Spha; and Cal.Con, Cal.Spha and Cal.SphaGB were compared using a paired BACI design. Statistics were carried out where the box and whisker plots indicated there might be significant differences. Differences between years were tested using Kruskal-Wallis independent samples test and Dunn-Bonferroni post-hoc tests.

5.3.2.1. *Calluna* site absorbance and colour

The calculated DOC concentration was modelled using all water samples taken from the CAL sites before intervention (including the spatial survey samples). The best model was found using three wavelengths (265, 360 and 400 nm):

$$DOC_{CAL} = 5.44 + (3.12 * abs_{400}) - (2.57 * abs_{360}) + (0.52 * abs_{265})$$

Equation 1: the modelled DOC concentration at CAL. N = 227; R² = 0.8592, adjusted R² = 0.8573

There were 633 water samples from *Calluna* that had both DOC and absorbance measured. The average modelled DOC concentration was 49.08 mg L⁻¹; the measured DOC concentration average was 45.98 mg L⁻¹. There were no significant differences between the modelled and measured DOC concentrations (paired t-test, p=0.14).

The residual DOC values were higher at higher measured DOC concentrations, suggesting the model had more realistic DOC concentrations when they were lower than 100 mg L⁻¹. As the majority of measured DOC concentrations were lower than 100 mg L⁻¹ (only 35 of 633 samples used in this analysis were more than 100 mg L⁻¹), equation 1 was used to model DOC in water samples from the *Calluna* site.

5.3.2.2. *Eriophorum* site absorbance and colour

The calculated DOC concentration was modelled using absorbance at four wavelengths: 470, 360, 265 and 254 nm:

$$DOC_{ERI} = 1.77 + (10.28 * abs_{470}) - (9.83 * abs_{360}) + (13.44 * abs_{265}) - (10.02 * abs_{254})$$

Equation 2: the modelled DOC concentration at ERI. N = 166, R² = 0.7442, adjusted R² = 0.7378

There were 453 water samples from *Eriophorum* that had both DOC and absorbance measured. The average modelled DOC concentration was 40.30 mg L⁻¹; the measured DOC concentration average was 38.48 mg L⁻¹. There were no significant differences between the modelled and measured DOC concentrations (paired t-test, p=0.90).

The residual DOC values were higher at higher measured DOC concentrations, suggesting the model had more realistic DOC concentrations when they were lower than 100 mg L⁻¹. As the majority of measured DOC concentrations were lower than 100 mg L⁻¹ (only 15 of 453 samples used in this analysis were more than 100 mg L⁻¹), equation 2 was used to model DOC in water samples from *Eriophorum*.

6. Results

6.1. Bare peat sites

The distribution of DOC concentration (raw and relative) were the same in all years at F and O. The distribution of relative DOC concentration at N was significantly different between years 0 and 13 – 2011 and 2024 (Mann Whitney U = 0, p=0.006). However, the small number of available samples in several of the years including 2024 (year 13) mean this finding should be treated with caution (see

Table 3 and discussion section below). The distribution of DOC relative load was the same in all years at F, O and N.

6.1.1. DOC concentration

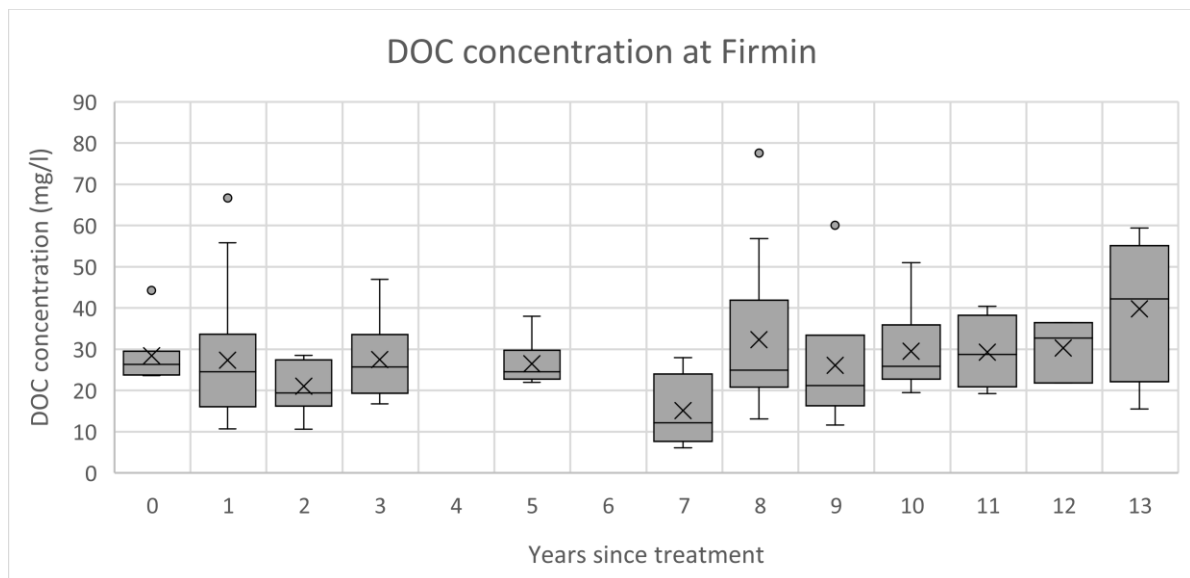


Figure 6. Box and whisker plot showing DOC concentration at F (bare peat control).

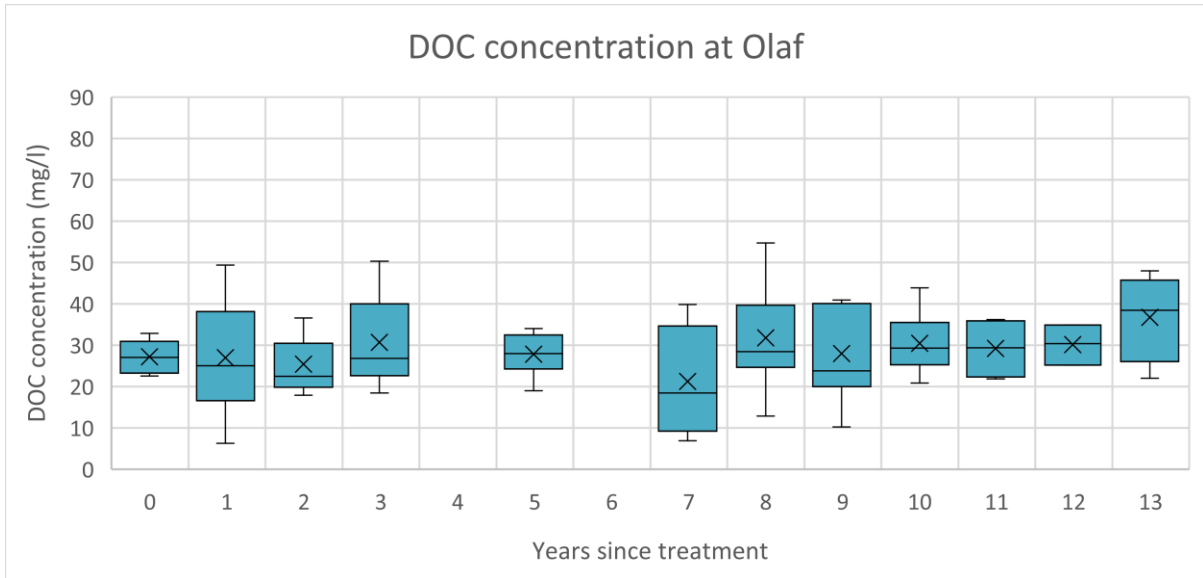


Figure 7. Box and whisker plot showing DOC concentration at O (revegetated site).

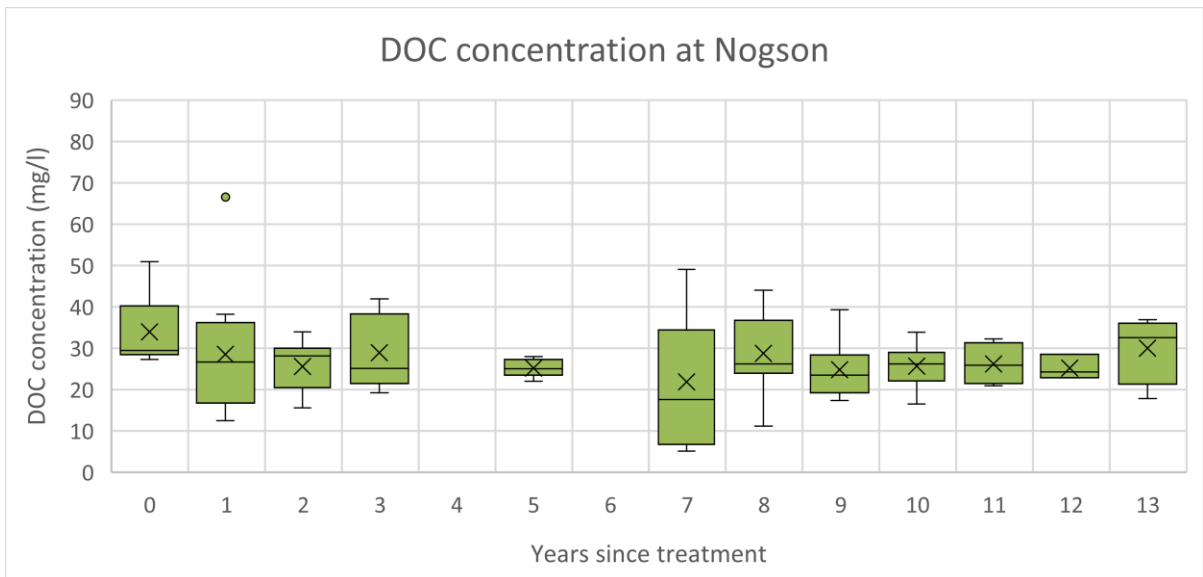


Figure 8. Box and whisker plot showing DOC concentration at N (revegetated, gully-blocked and Sphagnum-planted site).

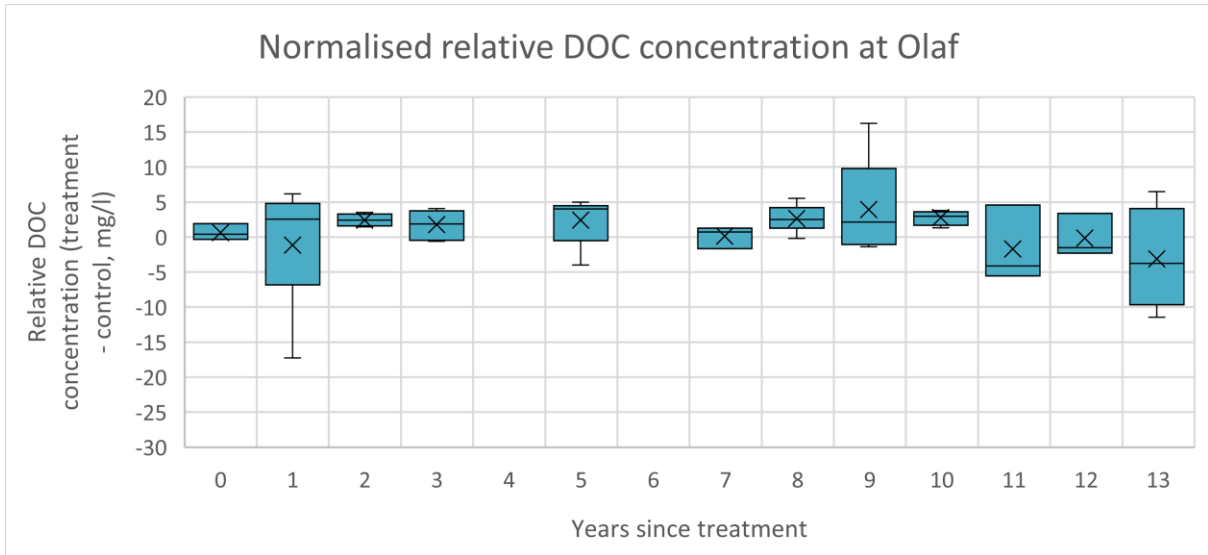


Figure 9. Box and whisker plot showing DOC concentration at O (revegetated site), relative to F (control). Median value for year 0 (before treatment) had been normalised to 0.

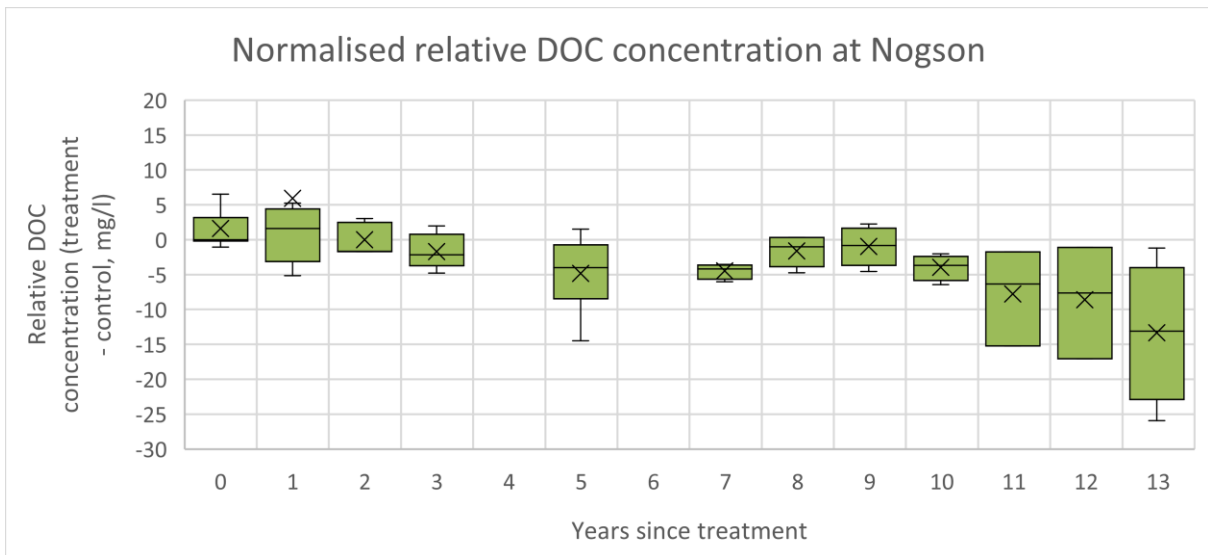


Figure 10. Box and whisker plot showing DOC concentration at N (revegetated, gully-blocked and *Sphagnum*-planted site), relative to F (control). Median value for year 0 (before treatment) had been normalised to 0.

Table 3. Summary statistics of DOC concentration at N relative to F (treatment – control). Note small number of paired samples available in years 7, 10, 11, 12 and 13.

Year	No. samples	Mean	Median	Std. Deviation	Minimum	Maximum	Range
0	7	5.1	3.48	2.71	2.44	9.98	7.54
1	8	9.39	5.08	17.15	-1.67	51.02	52.69
2	5	3.48	1.84	2.32	1.78	6.53	4.75
3	6	1.79	1.31	2.51	-1.32	5.46	6.77
5	6	-1.33	-0.5	5.47	-11	5	16
7	4	-0.99	-0.68	1.1	-2.53	-0.07	2.46
8	6	1.87	2.48	2.13	-1.24	3.8	5.04
9	5	2.5	2.63	2.77	-1.07	5.75	6.82
10	4	-0.47	-0.18	1.85	-2.97	1.45	4.42
11	3	-4.3	-2.87	6.85	-11.75	1.71	13.46
12	3	-5.12	-4.14	8.04	-13.6	2.39	15.99
13	4	-9.85	-9.61	10.13	-22.46	2.3	24.76

6.1.2. DOC load

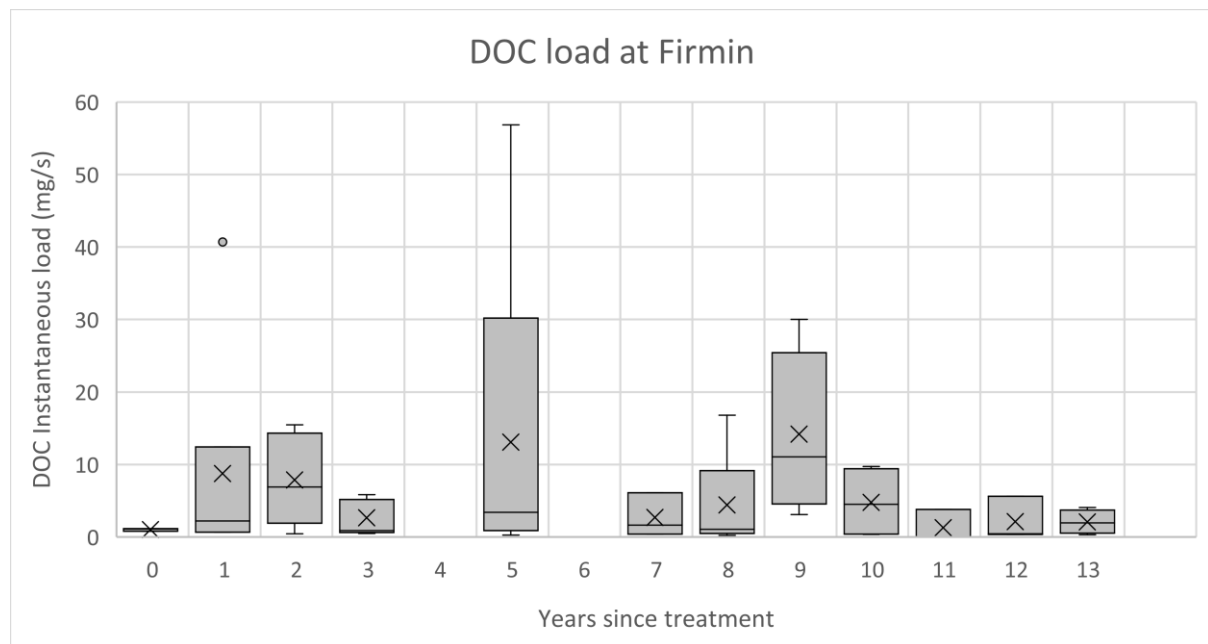


Figure 11. Box and whisker plot showing DOC instantaneous load at F (bare peat control).

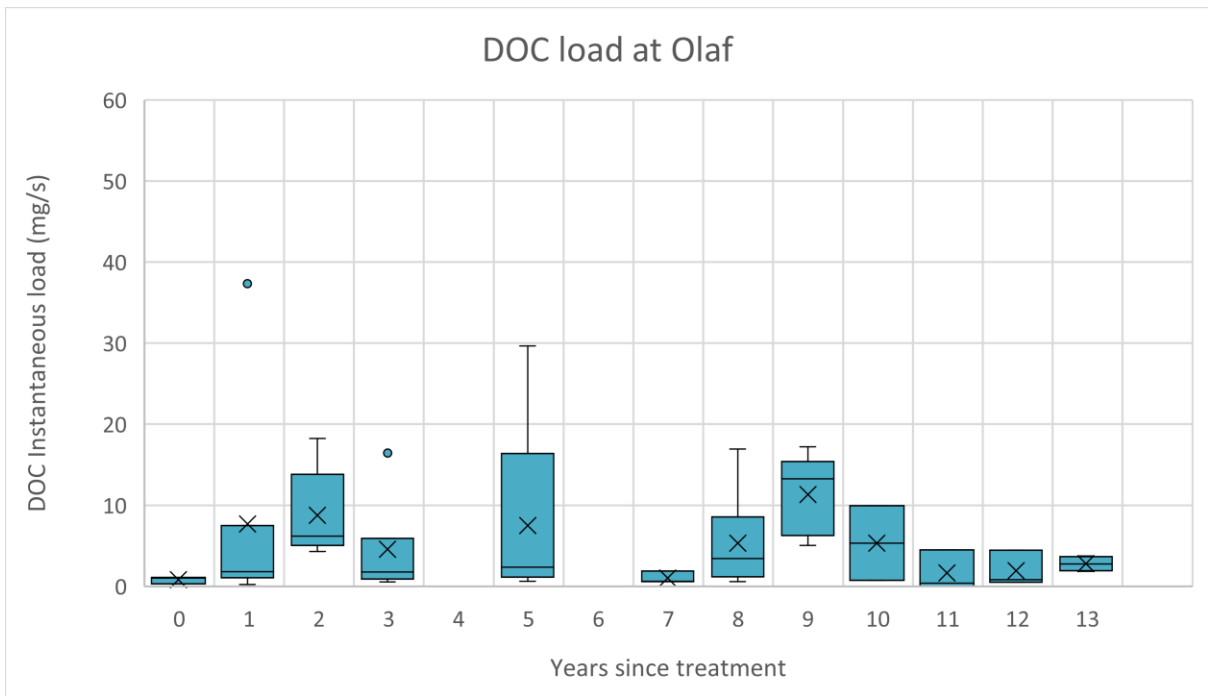


Figure 12. Box and whisker plot showing DOC instantaneous load at O (revegetated site).

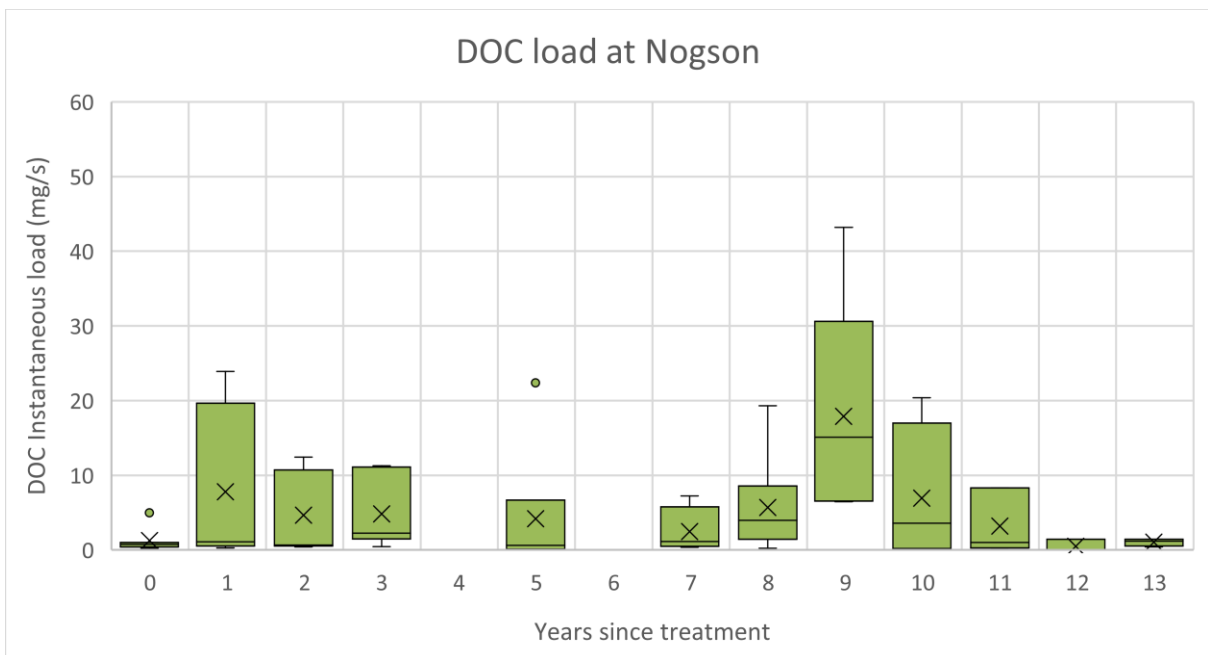


Figure 13. Box and whisker plot showing DOC instantaneous load at N (revegetated, gully-blocked and Sphagnum-planted site).

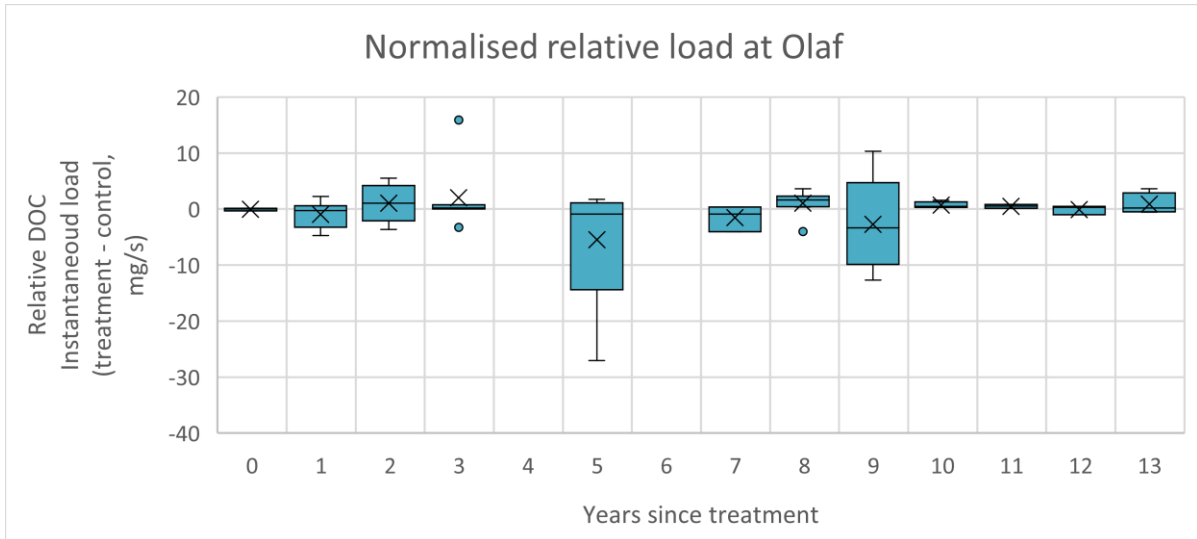


Figure 14. Box and whisker plot showing relative (treatment-control) DOC instantaneous load at O (revegetated site). Positive values indicate higher DOC load at treatment than at control. Median value for year 0 (before treatment) had been normalised to 0.

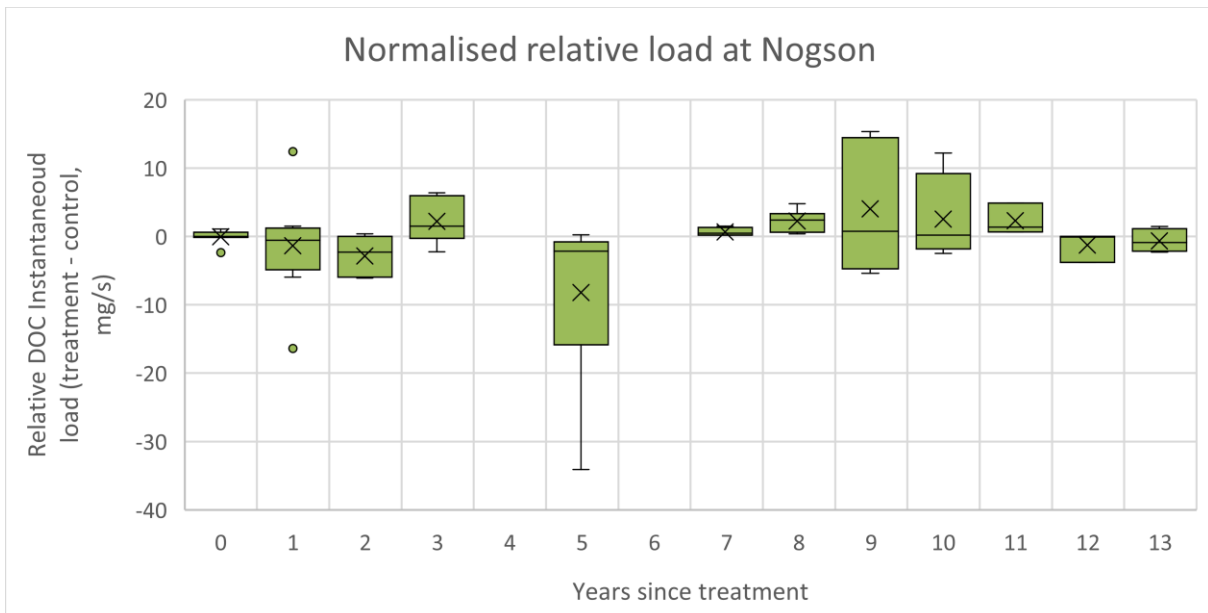


Figure 15. Box and whisker plot showing relative (treatment-control) DOC instantaneous load at N (revegetated, gully-blocked and *Sphagnum*-planted site). Positive values indicate higher DOC load at treatment than at control. Median value for year 0 (before treatment) had been normalised to 0.

6.1.3. DOC concentration (individual samples)

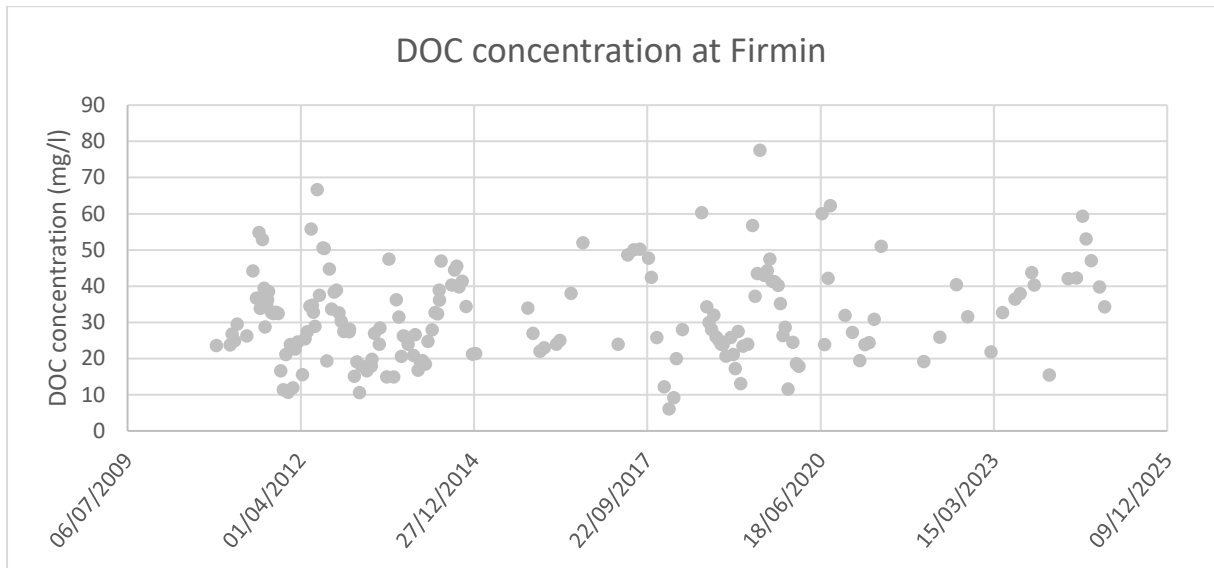


Figure 16. DOC concentration at F (bare peat control) showing all individual samples.

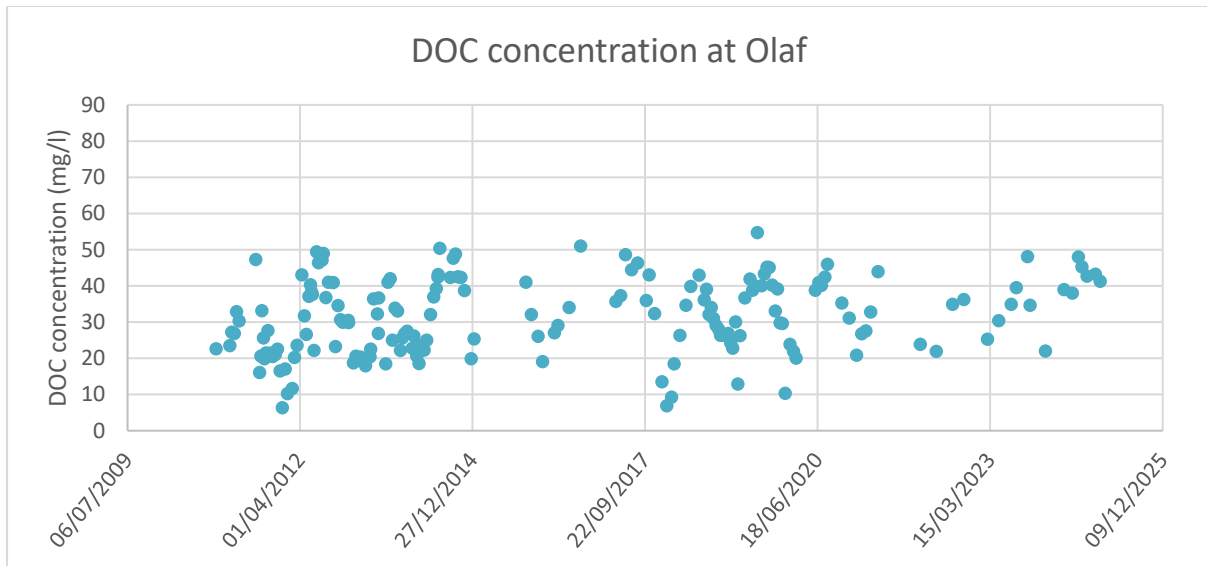


Figure 17. DOC concentration at O (revegetated site) showing all individual samples.

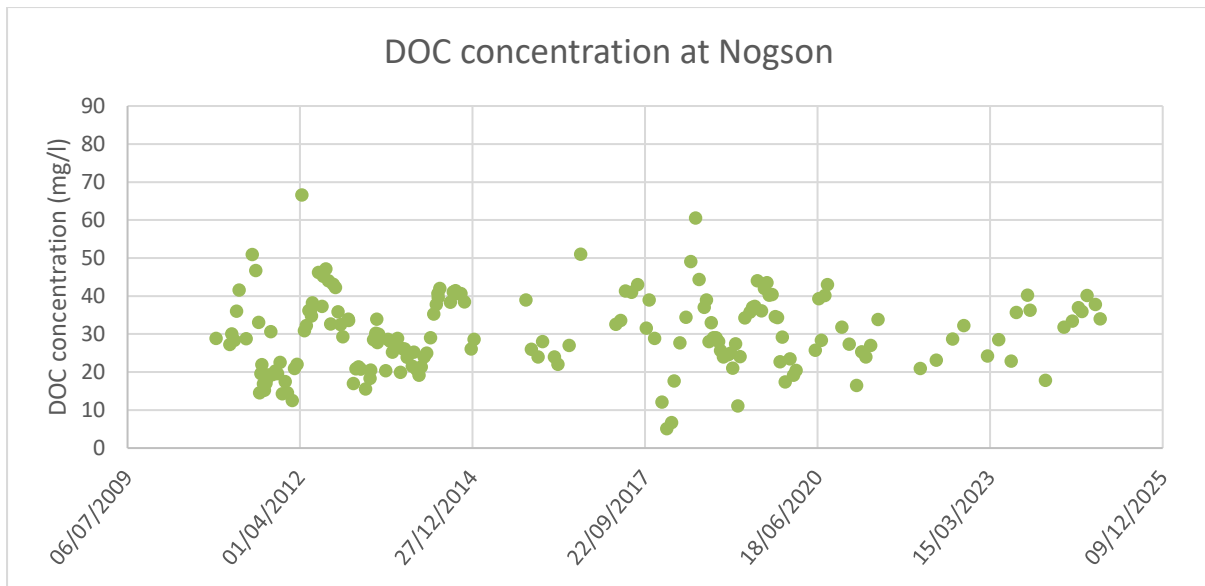


Figure 18. DOC concentration at N (revegetated, gully-blocked and *Sphagnum*-planted site) showing all individual samples.

6.2. Species-dominated sites

6.2.1. Calluna site

No change was detected in DOC concentration (raw or relative) at either the control or treatment sites. No change in DOC load (raw or relative) was detected at either the control or treatment sites. The largest difference noted in relative load was at Cal.Spha between post-treatment years 2 and 4, but this was not statistically significant (Kruskal-Wallis $H=13.64$, Adj. $p = 0.582$).

6.2.1.1. DOC concentration

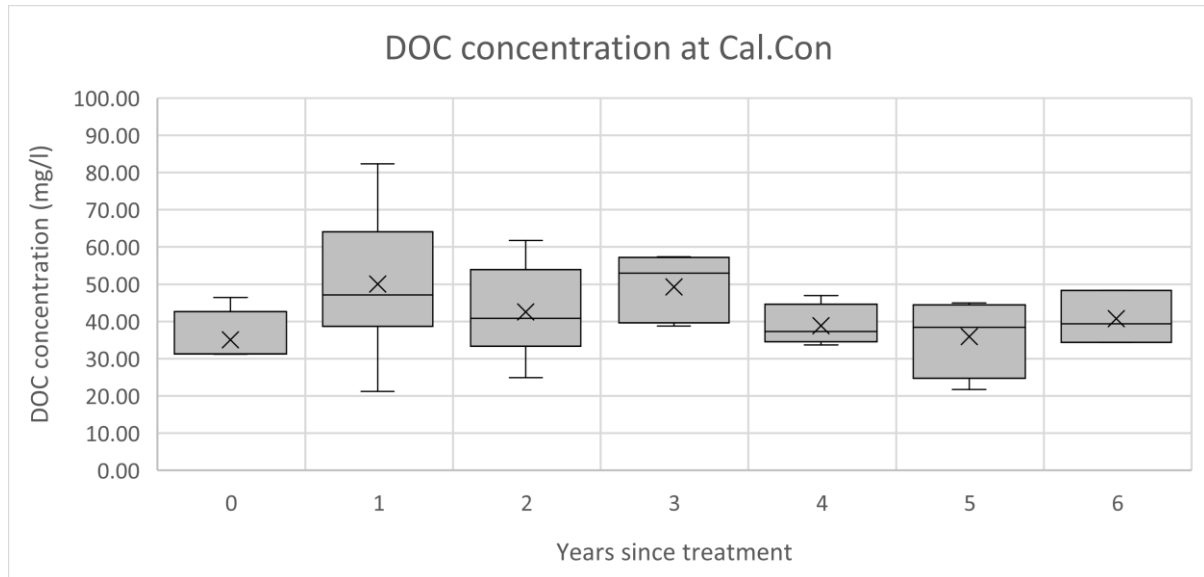


Figure 19. Box and whisker plot showing DOC concentration at Cal.Con (heather-dominated control).

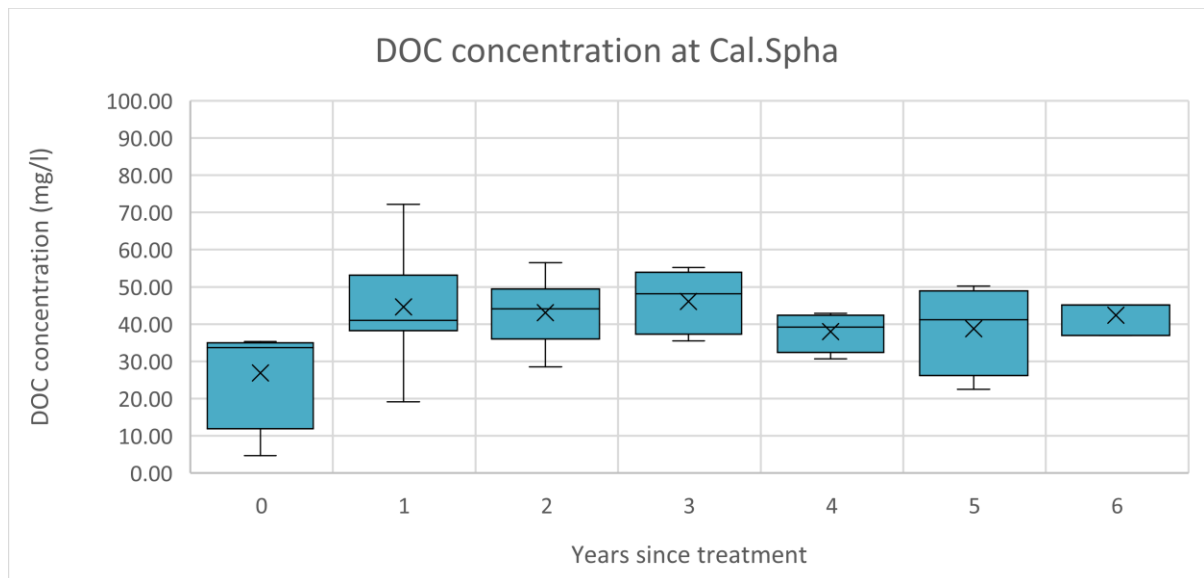


Figure 20. Box and whisker plot showing DOC concentration at Cal.Spha (heather-dominated, *Sphagnum*-planted site).

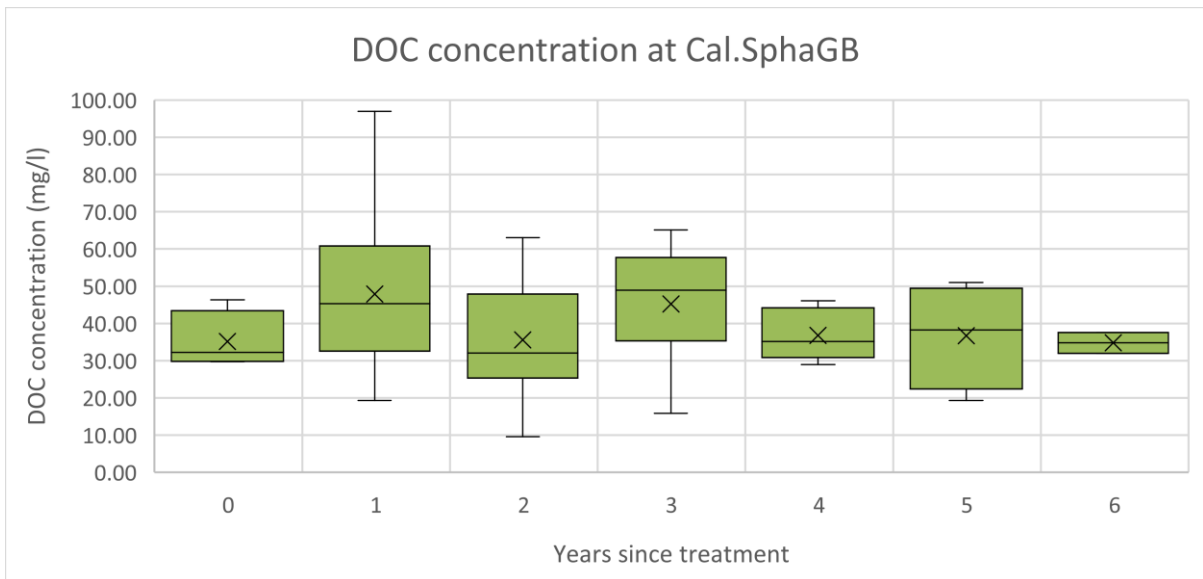


Figure 21. Box and whisker plot showing DOC concentration at Cal.SphaGB (heather-dominated, Sphagnum-planted, gully-blocked site).

6.2.1.2. DOC load

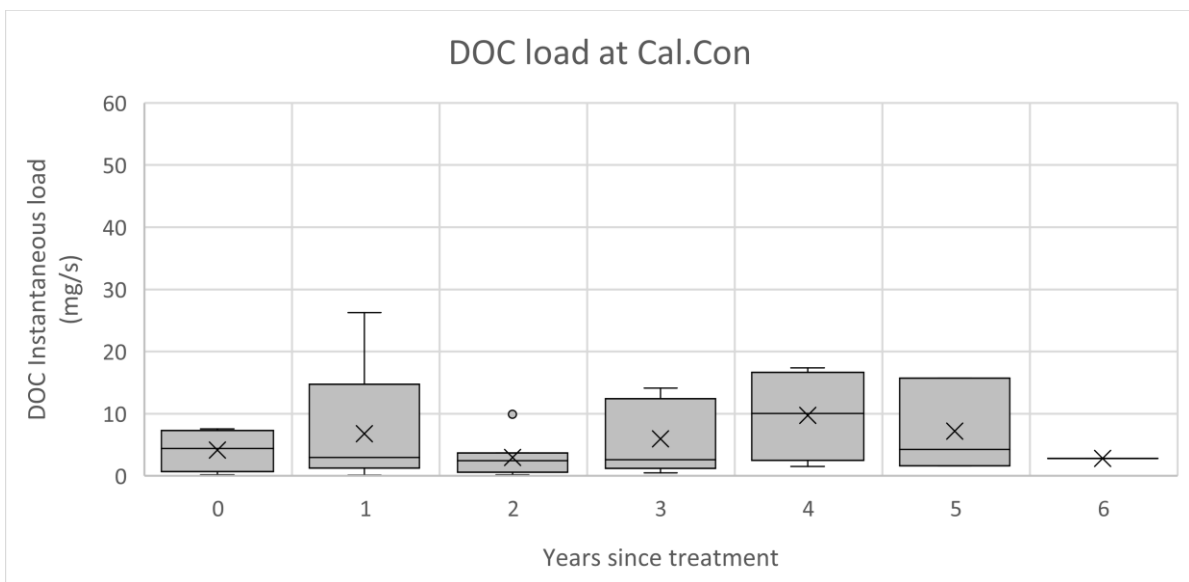


Figure 22. Box and whisker plot showing DOC instantaneous load at Cal.Con (heather-dominated control).

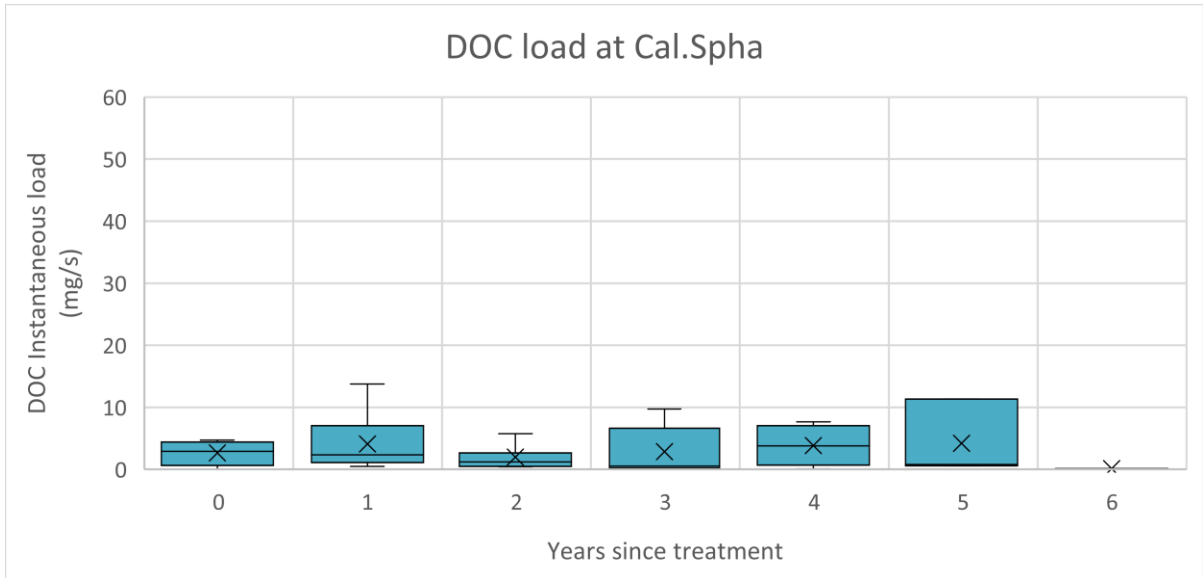


Figure 23. Box and whisker plot showing DOC instantaneous load at Cal.Spha (heather-dominated, Sphagnum-planted site).

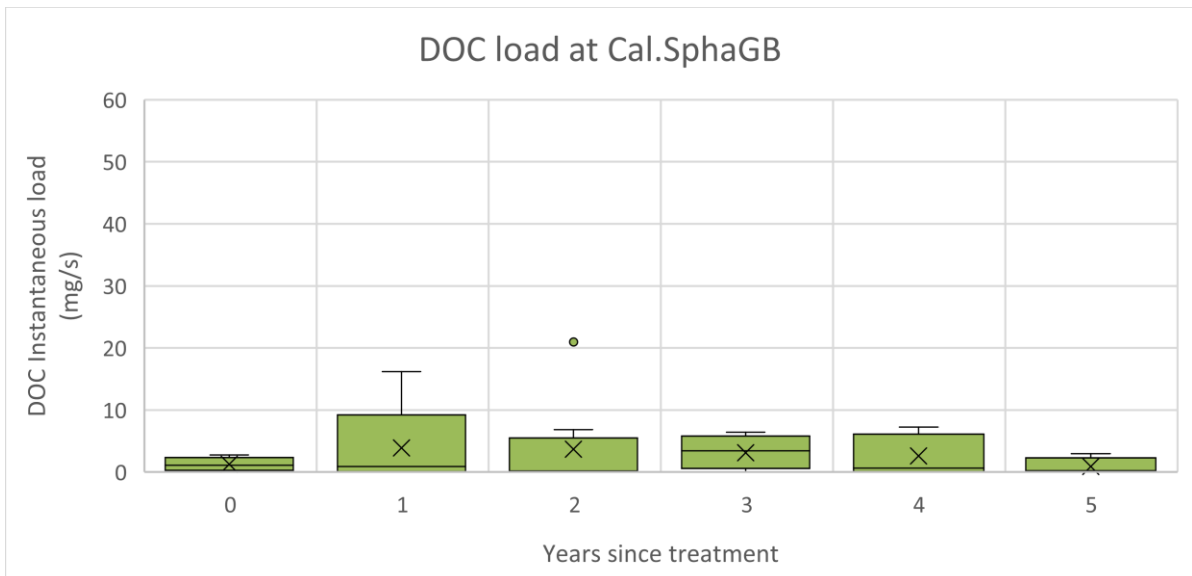


Figure 24. Box and whisker plot showing DOC instantaneous load at Cal.SphaGB (heather-dominated, Sphagnum-planted, gully-blocked site).

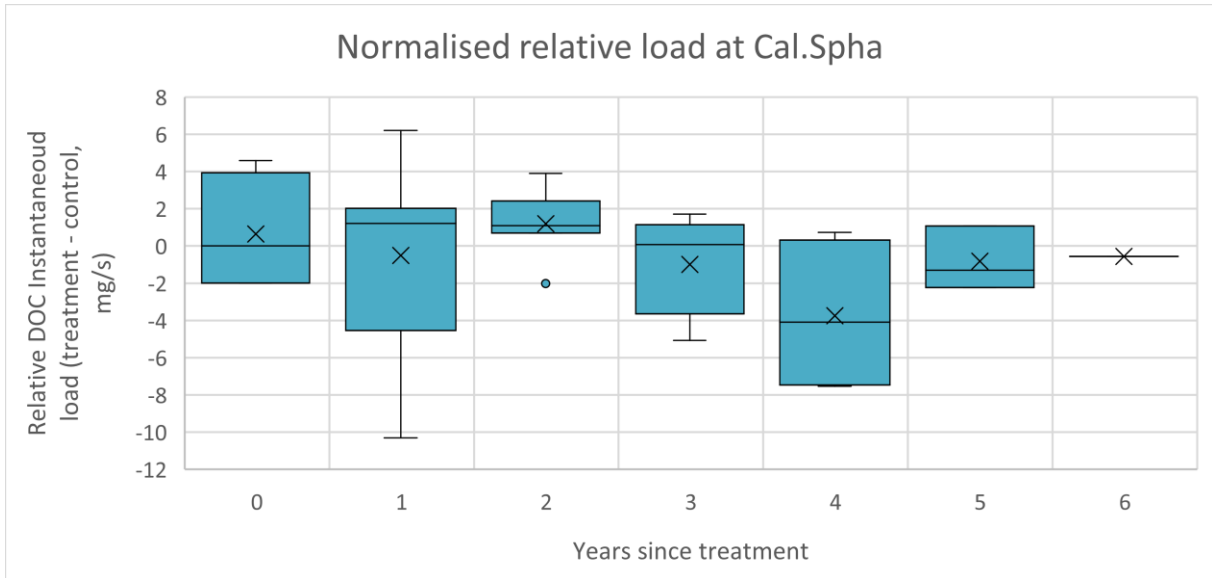


Figure 25. Box and whisker plot showing relative (treatment-control) DOC instantaneous load at Cal.Spha (heather-dominated, *Sphagnum*-planted site). Positive values indicate higher DOC load at treatment than at control. Median value for year 0 (before treatment) had been normalised to 0.

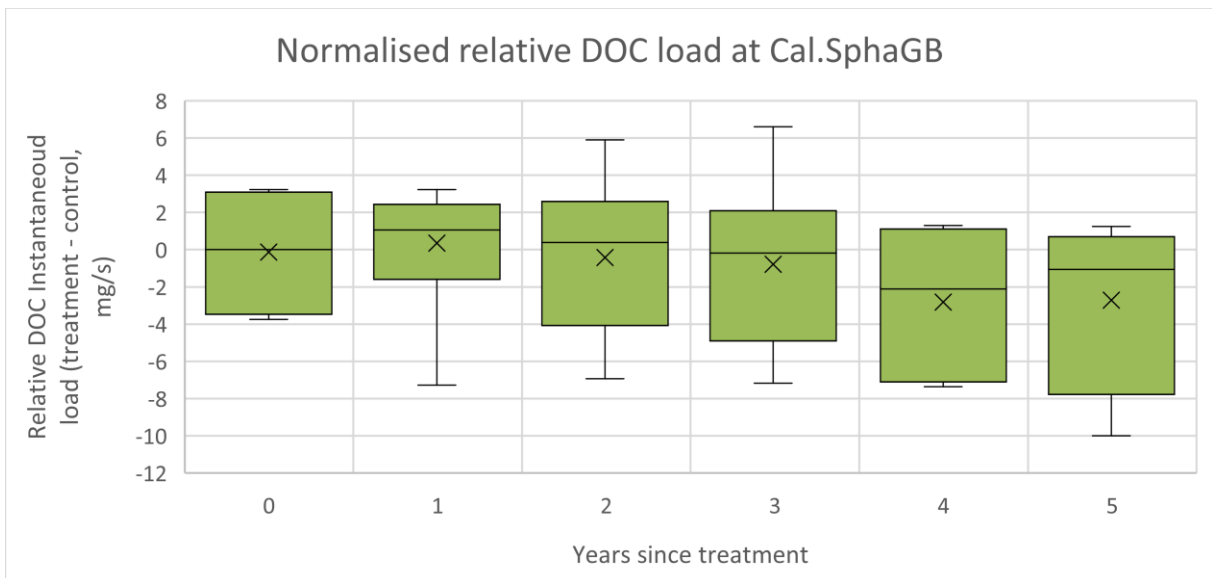


Figure 26. Box and whisker plot showing relative (treatment-control) DOC instantaneous load at Cal.SphaGB (heather-dominated, *Sphagnum*-planted, gully-blocked site). Positive values indicate higher DOC load at treatment than at control. Median value for year 0 (before treatment) had been normalised to 0.

6.2.1.3. DOC concentration (individual samples)

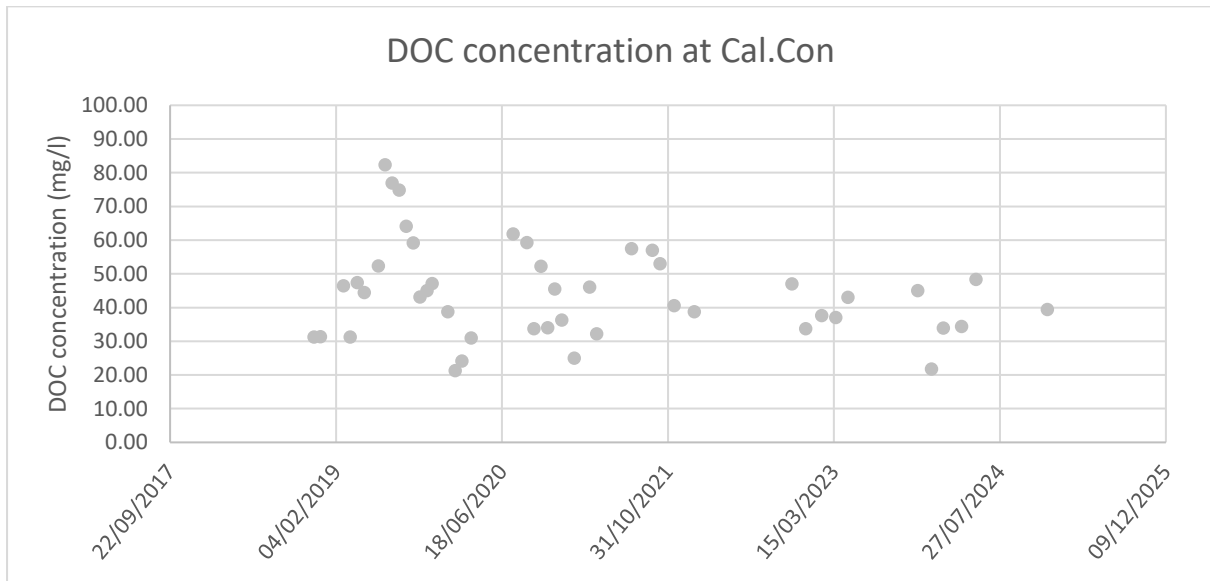


Figure 27. DOC concentration at Cal.Con (heather-dominated control) showing all individual samples.

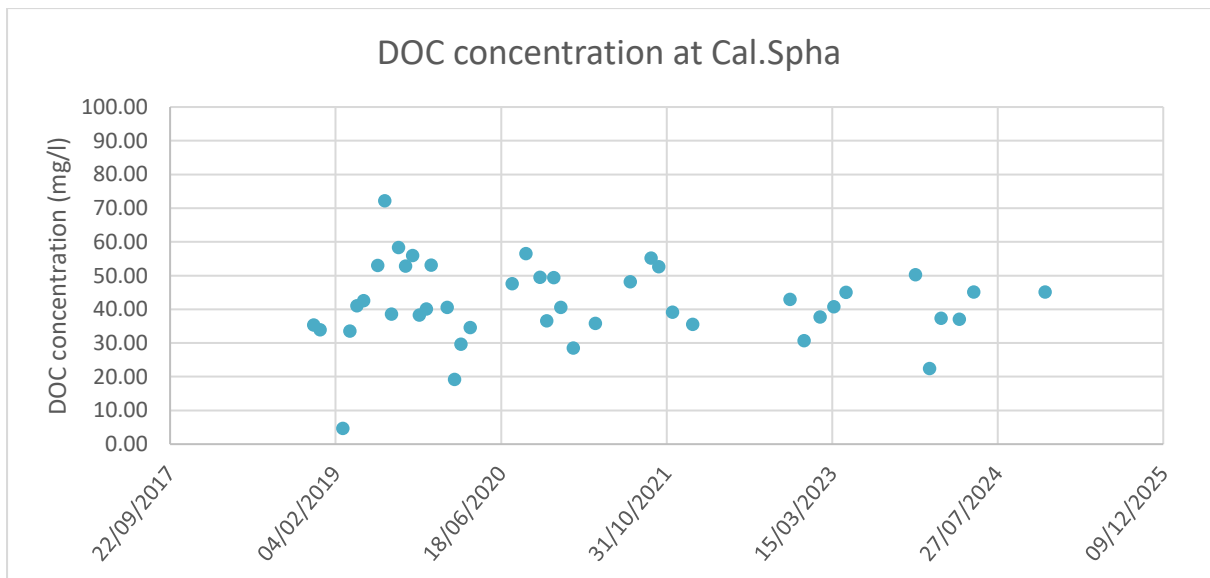


Figure 28. DOC concentration at Cal.Spha (heather-dominated, *Sphagnum*-planted site) showing all individual samples.

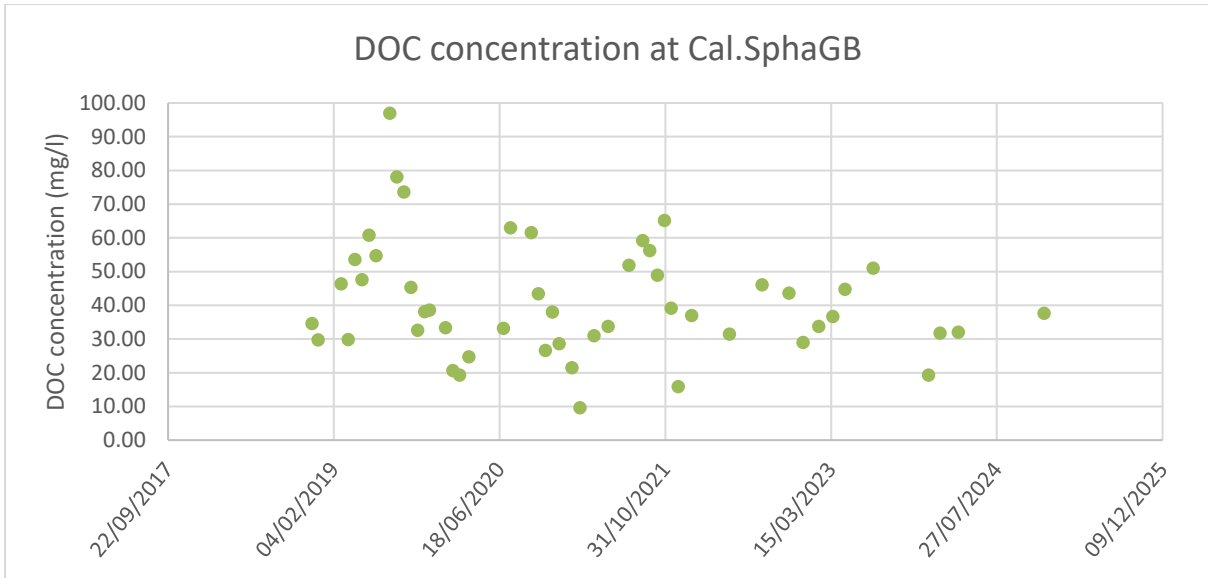


Figure 29. DOC concentration at Cal.SphaGB (heather-dominated, *Sphagnum*-planted, gully-blocked site) showing all individual samples.

6.2.2. Eriophorum site

No change was detected in DOC concentration (raw or relative) at either the control or treatment sites. No change in DOC load (raw or relative) was detected at either the control or treatment site. The largest differences noted in relative load were between post-treatment years 1–3, 2–3 and 3–6, but these were not statistically significant (Kruskal-Wallis Adj $p = >0.05$ in all cases). Year 6 had a low number ($n = 3$) of viable paired load samples available to test, so results for this year should be treated with caution.

6.2.2.1. DOC concentration

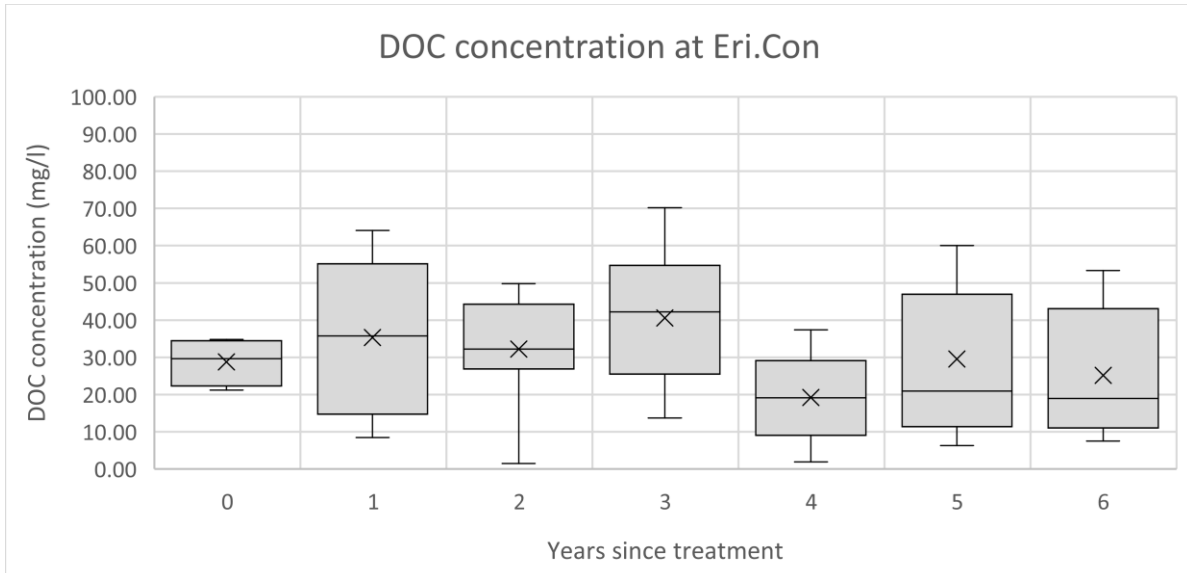


Figure 30. Box and whisker plot showing DOC concentration at Eri.Con (cotton-grass-dominated control).

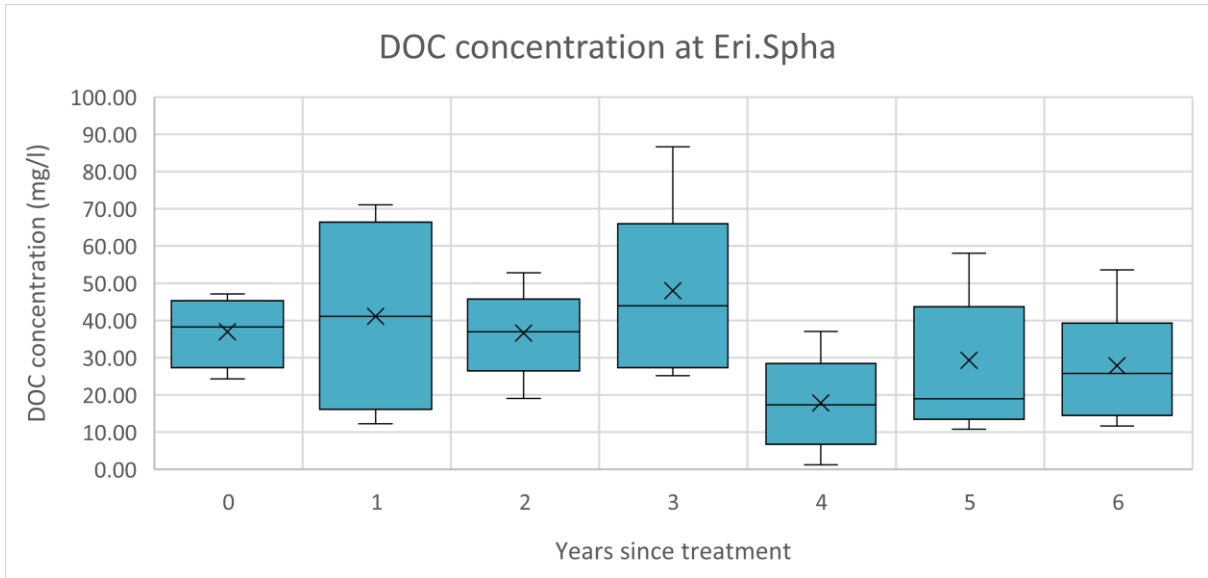


Figure 31. Box and whisker plot showing DOC concentration at Eri.Spha (cotton-grass-dominated control).

6.2.2.2. DOC load

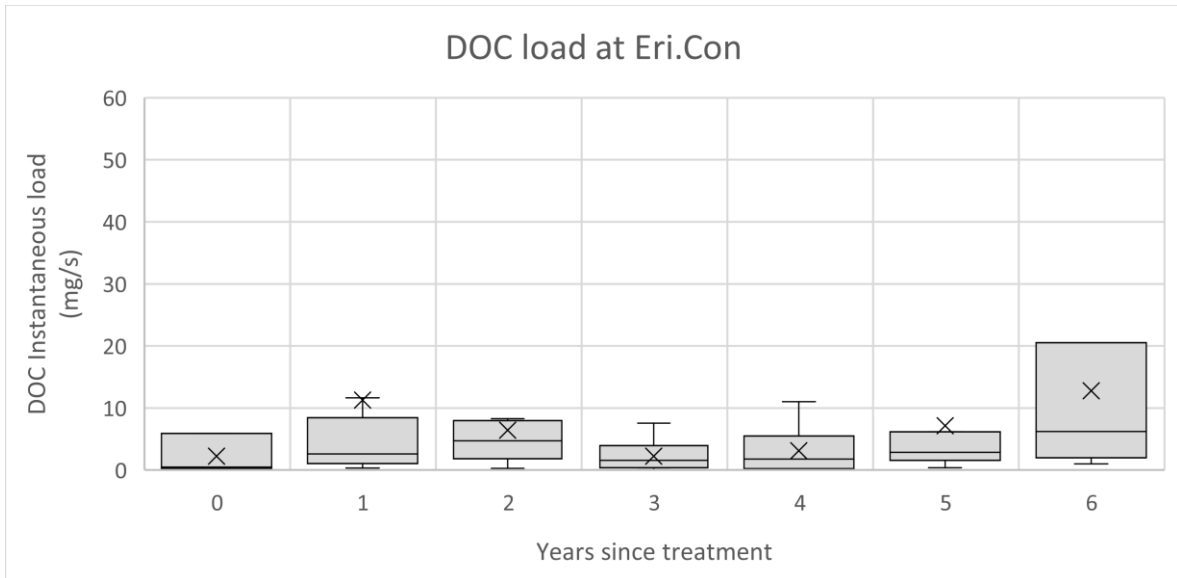


Figure 32. Box and whisker plot showing DOC instantaneous load at Eri.Con (cotton-grass-dominated control).

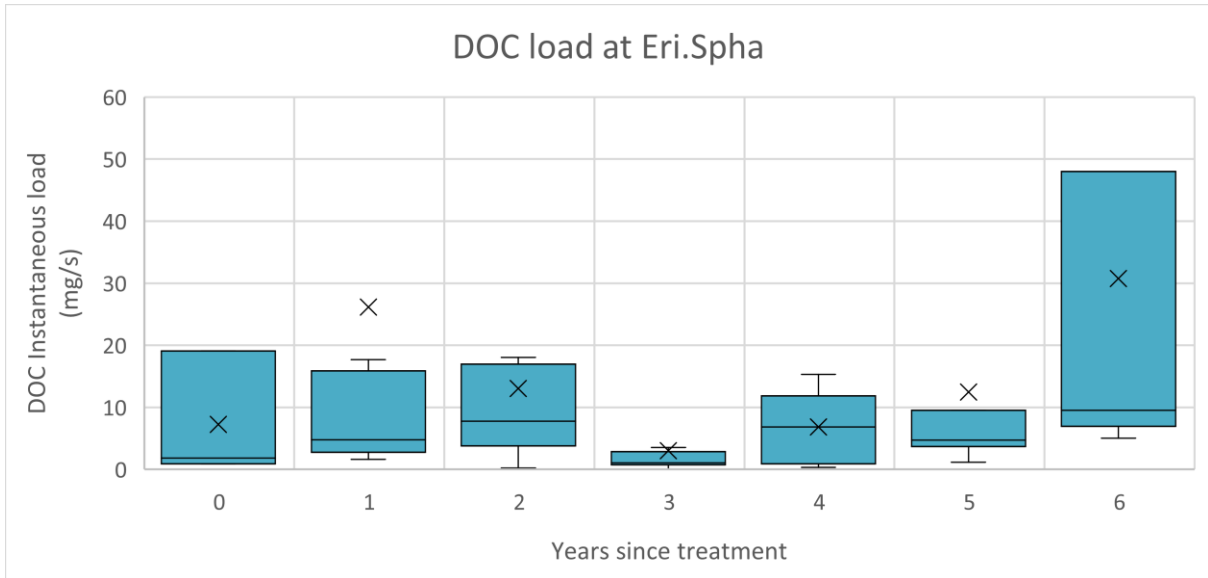


Figure 33. Box and whisker plot showing DOC instantaneous load at Eri.Spha (cotton-grass-dominated, *Sphagnum*-planted site).

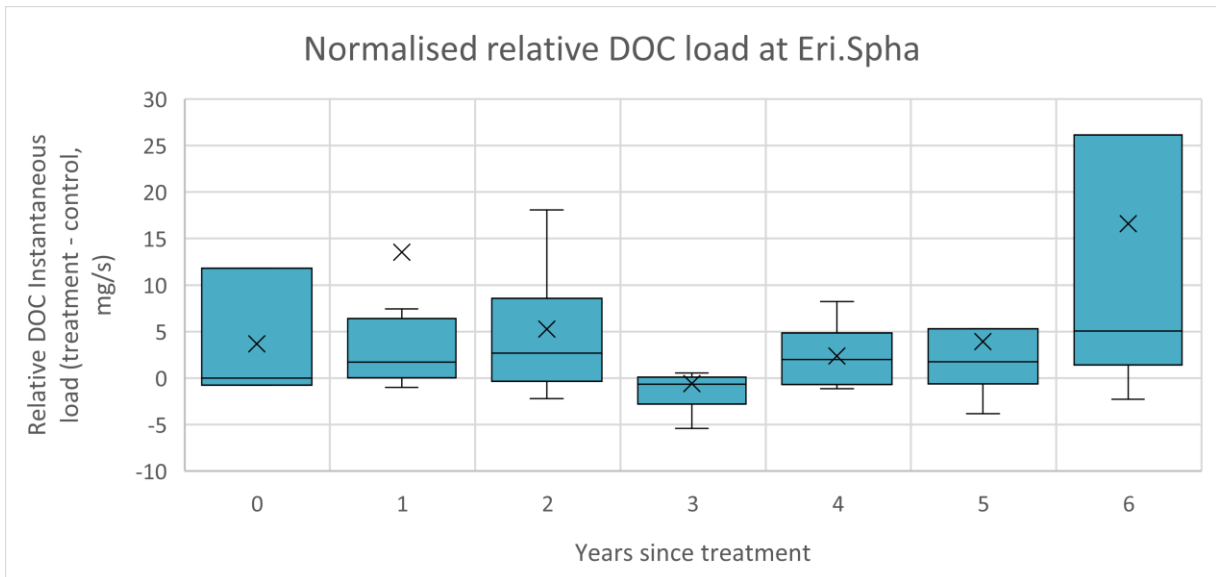


Figure 34. Box and whisker plot showing relative (treatment-control) DOC instantaneous load at Eri.Spha (cotton-grass-dominated, *Sphagnum*-planted site). Positive values indicate higher DOC load at treatment than at control. Median value for year 0 (before treatment) had been normalised to 0.

6.2.2.3. DOC concentration (individual samples)

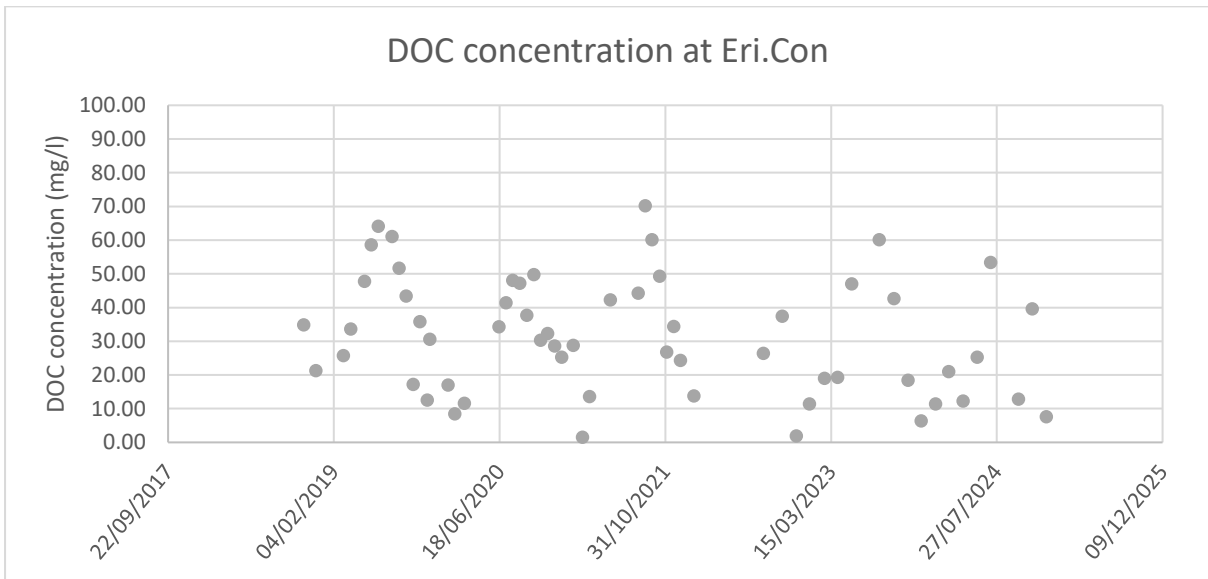


Figure 35. DOC concentration at Eri.Con (cotton-grass-dominated control) showing all individual samples.

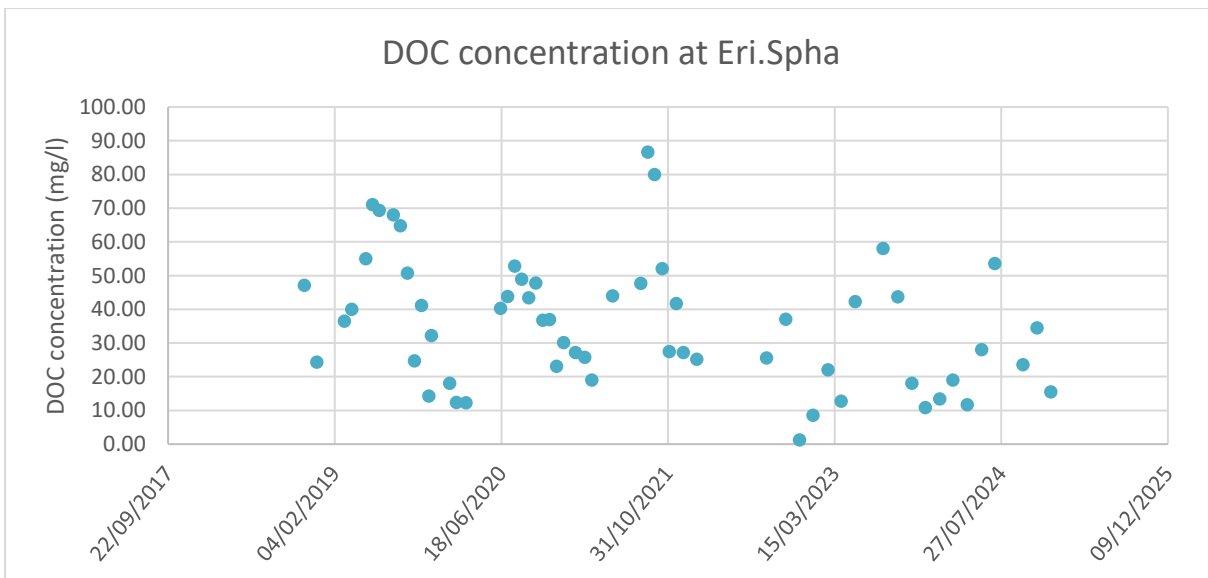


Figure 36. DOC concentration at Eri.Spha (cotton-grass-dominated, *Sphagnum*-planted site) showing all individual samples.

7. Discussion

7.1. Bare peat sites

As discussed in the MoorLIFE 2020 D2 report (Evans et al., 2022), previous work on the data from the first five years of monitoring indicated short-term reductions (up to 6 months) in DOC concentration at the treatment sites associated with the application of lime which is hypothesised to relate to the flocculating effect of calcium ions (Stimson *et al.* 2017). At the longer timescale assessed through the ML2020 and Moor Water projects, no consistent long-term change in DOC load was observed at any of the field labs during the monitoring period. It is important to note that the deep gullies across these sites are the macro-scale control on water table for gully edge sites (Allott *et al.* 2009) and that this is relatively unaffected by gully blocks the height of which is only circa 20% of gully depth. The restoration results seen in this work produce excellent restoration of the moorland vegetation but these are still modified systems, so it is likely that lowered water tables at gully edges are still the dominant control on DOC concentration.

However, a potential decreasing trend in DOC concentration was observed at N (revegetated, *Sphagnum*-planted and gully-blocked site) when it was compared to the untreated bare peat control site at F, as seen Figure 10. The median relative concentration in year 13 (2024) was ~13 mg/l lower than during the baseline year (2011). This result did not coincide with an increase in discharge during low-flow conditions which remained broadly stable over time, and the change was not observed in the results for DOC load (mg/s) exiting the mini-catchment. The timing of the decrease did however coincide with a number of factors which should be considered: (i) A large estimated increase in *Sphagnum* area coverage in flow pathways at N during recent years (~90% cover by 2022, up from ~16% cover in 2018). It is probable that *Sphagnum* depth has also increased, although this has not yet been quantified. Possible mechanisms by which this could impact DOC concentration include further localised reduction of POC generation within the channel, and an increased residence time of water in the *Sphagnum*-rich channels, altering microbial activity. However, there are also many other factors (dilution by volume of water for example) which could interact and contribute to changes in DOC concentration. The mechanism at work here if the difference found is indeed real, is as yet unclear. (ii) The changes seen between 2021–2024 broadly coincided with a return to modelling DOC rather than direct measurement of DOC. (iii) During these years small numbers of paired samples (for example only 4 in 2024) were available to analyse, particularly to calculate DOC load – due to factors including dry periods with no flow coinciding with routine monitoring visits. These small sample sizes mean it is difficult to draw firm conclusions, and the result found at N should be treated with caution. Future sampling is required to assess if the difference seen here is part of a trend or an anomaly. A higher frequency of sampling along with a return to measuring rather than modelling DOC should be considered.

7.2. Species-dominated sites

As discussed in the MoorLIFE 2020 D2 report (Evans et al., 2022), previous work on the data from the first three years of monitoring indicated possible changes to DOC character were observed in the water at the weirs, although no changes were statistically significant. However, in this study, DOC concentration and load only were modelled using the same formulae used in the MoorLIFE 2020 work.

Results from the study at the *Calluna* site and the *Eriophorum* site found no clear changes in DOC concentration or load six years after treatment. As above it is likely that the deep gullying present at both sites (particularly the *Calluna* site) is the main control on water table on these sites, which may in turn be one of the dominant controls on DOC concentration. Vegetation was monitored at both

sites in areas where *Sphagnum* plugs had been planted at a density of 4 per m². At the *Eriophorum*-dominated treatment site Eri.Spha, *Sphagnum* cover increased from 0% in 2018 to ~10% in 2024; at the *Calluna*-dominated treatment site Cal.Spha, *Sphagnum* cover increased from 0% in 2018 to ~30% in 2024; at the *Calluna*-dominated treatment site Cal.SphaGB *Sphagnum* cover increased from 0% in 2018 to ~17% in 2024. However, on these sites, *Sphagnum* cover in flow pathways has not been quantified as at the bare peat site N. Anecdotally, it appears to be lower in the flow pathways than the figures above may suggest. Work on POC flux on the *Calluna* site in 2020 showed that Cal.Spha had some large areas of bare peat (20 – 50% of gully sides) in the main gully leading to the weir, and indeed these sections produced significantly more sediment transport than the Control or SphaGB mini-catchments. These areas of bare peat do not appear to have changed since 2020, nor does the cover of the dominant vegetation types despite an overall (though not uniform) increase in *Sphagnum*.

7.3. Limitations

The data presented in this study are from water samples collected during routine visits to the field sites, generally in low flow conditions. It was therefore not possible to assess any impacts of treatment on DOC generation in high flow conditions, when accumulated DOC may be flushed from the system. The limited number of paired samples available, also mean that it is difficult to draw firm conclusions from the data collected during the monitoring period due to small sample sizes. On the species-dominated sites, the period before treatment was short, meaning a full year of samples was not available be used for year '0' (Before) in the analysis.

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

8. Conclusions

8.1. Bare peat sites

The dramatic habitat restoration achieved by the project has not led to clear divergence of DOC concentration or flux between the control sites and the treatment sites. Over the five years of MoorLIFE 2020 and four years of Moor Water without further application of lime, DOC load appears stable. However, a possible decrease in relative DOC concentration at the treatment site Nogson (revegetated, gully-blocked and with extensive 90%+ *Sphagnum* cover in flow pathways) in 2024 is worthy of further investigation. An increased sampling frequency, along with sampling in storm conditions with an autosampler would provide a valuable addition to this long running dataset which may enable an understanding of the results found in 2024.

8.2. Species-dominated sites

Data collected over the period of the MoorLIFE 2020 study and the Moor Water study did not suggest a clear divergence in DOC concentration and load between the control and treatment sites at either the *Calluna*- or *Eriophorum*-dominated sites. However, the smaller number of paired samples available in recent years due to the reduced sampling frequency afforded during by the Moor Water period of the study mean that it was more difficult to interpret results than the previous period which has seen fortnightly sample collection. For both sites an increase in future sampling frequency would be desirable.

9. References

- Allott, T. E. H.; Evans, M. G.; Lindsay, J. B.; Agnew, C. T.; Freer, J. E.; Jones, A.; Parnell, M. (2009) Water Tables in Peak District Blanket Peatlands; Moors for the Future Report No. 17; Edale, U.K.
- Armstrong A, Holden J, Luxton K, Quinton JN. (2012) Multi-scale relationship between peatland vegetation type and dissolved organic carbon concentration. *Ecological Engineering*. Oct 1;47:182-8.
- Buckler, M., Proctor, S., Walker, J.S., Wittram, B., Straton, P. and Maskill, R.M. (2013) Moors for the Future Partnerships restoration methods for restoring bare peat in the South Pennines SAC: evidence-based recommendations Moors for the Future Partnership, Edale.
- Bussell, J., Jones, D.L., Healey, J.R., and Pullin, A.S. (2010) how do draining and re-wetting affect carbon stores and greenhouse gas fluxes in peatland soils? Systematic Review CEE 08-012 (SR 49), Centre for Evidence-Based Conservation School of Environment, Natural Resources and Geography
- Caporn S., Carroll J.A., Studholme C., Lee J.A. (2006) *Recovery of ombrotrophic Sphagnum mosses in relation to air pollution in the Southern Pennines*. Report to Moors for the Future
- Caporn, S., Sen, R., Field, C., Jones, E., Carroll, J., Dise, N. (2007). Consequences of lime and fertiliser application for moorland restoration and carbon balance. Research report to Moors for the Future.
- Evans, M., Stimson, A., Allott, T., Pilkington, M., Shuttleworth, E., Holland, N., Spencer, T., Walker, J. (2015). Annex 4: Dissolved Organic Carbon concentrations. In Pilkington M.G. *et al.* (2015) Restoration of Blanket bogs; flood risk reduction and other ecosystem benefits. Final report of the Making Space for Water project: Moors for the Future Partnership, Edale.
- Evans, M.G, Margetts, J.J., Moody, C.S., Pilkington M.G., Ritson, J.P, Spencer T. (2022). *Chapter 6: Water Chemistry in Moors for the Future Partnership (2022) Monitoring the biodiversity and ecosystem service impacts of restoration of degraded blanket bog sites*. Final report of the MoorLIFE 2020 project Action D2: Moors for the Future Partnership, Edale.
- Margetts, J.J., Pilkington, M.G. and Spencer T. (2022). *Chapter 2: Background, project area, restoration, monitoring design and climate* In Moors for the Future Partnership (2022) *Monitoring the biodiversity and ecosystem service impacts of restoration of degraded blanket bog sites*. Final report of the MoorLIFE 2020 project Action D2: Moors for the Future Partnership, Edale.
- Monteith, D.T., Henrys, P.A., Evans, C.D, Malcolm, I., Shilland, E.M., Pereira, M.G. (2015). Spatial controls on dissolved organic carbon in upland waters inferred from a simple statistical model *Biogeochemistry* DOI 10.1007/s10533
- Ritson JP, Brazier RE, Graham NJ, Freeman C, Templeton MR, Clark JM. (2017) The effect of drought on dissolved organic carbon (DOC) release from peatland soil and vegetation sources. *Biogeosciences*. 2017 Jun 16;14(11):2891-902.
- Rothwell, J.J., Evans, M.G., Daniels, S.M., Allott, T.E.H. (2007) Baseflow and stormflow metal concentrations in streams draining contaminated peat moorlands in the Peak District National Park (UK). *Journal of Hydrology* (2007) 341, 90– 104
- Spencer, T., Evans, M. (2016). Water quality trajectories on bare peat stabilisation sites. Report for Moors for the Future Partnership, Edale.

Stimson, A.G. (2015). Fluvial carbon dynamics in degraded peatland catchments. A thesis submitted to The University of Manchester for the degree of Doctor of Philosophy in the Faculty of Humanities

Stimson, A.G., Allott, T.E.H., Boulton, S., and Evans, M.G. (2017) Fluvial organic carbon composition and concentration variability within a peatland catchment – implications for carbon cycling and water treatment. In press in *Hydrological Processes* DOI 10.1002/hyp.113522017

Stimson, A.G., Allott, T.E.H., Boulton, S., Evans, M.G., Pilkington, M. and Holland, N. Water quality impacts of bare peat revegetation with lime and fertiliser application. *Applied Geochemistry* 85 97-100

Strack M, Tóth K, Bourbonniere R, Waddington JM. (2011) Dissolved organic carbon production and runoff quality following peatland extraction and restoration. *Ecological Engineering*. 2011 Dec 1;37(12):1998-2008.

Strack M, Zuback Y, McCarter C, Price J. (2015) Changes in dissolved organic carbon quality in soils and discharge 10 years after peatland restoration. *Journal of Hydrology*. 2015 Aug 1;527:345-54.

Wallage, Z.E., Holden, J., McDonald, A.T. (2006). Drain blocking: An effective treatment for reducing dissolved organic carbon loss and water discolouration in a drained peatland. *Science of The Total Environment* 367, 811–821. doi:10.1016/j.scitotenv.2006.02.010

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