CARBON MODELLING
PHASE 3

MoorLIFE 2020

MoorLIFE 2020 Carbon modelling – Phase 3

Suggested citation:
Worrall, F., (2022) MoorLIFE 2020 Carbon modelling Phase 3 report, Durham University

Prepared by Fred Worrall

Dept of Earth Sciences,
University of Durham,
Sciene Laboratories,
South Road,
Durham,
DH1 3LE.

1st September 2022

EXECUTIVE SUMMARY

This Phase 3 report is an update and extension of reports previously presented. Because of the problems found in Phase 2, namely, the problem of assigning vegetation to restoration areas, in this phase we take an alternative approach to ensure consistency between the modelling of restored areas. We quantify the greenhouse gas benefits of the restoration works conducted by the MoorLIFE2020 project, and specifically provide:

- The development of a lookup table approach to understand the carbon and greenhouse gas exports and budgets for use on the peatlands of the South Pennine Moors Special Area of Conservation and Peak District National Park.
- The application of the look up table approach to the MoorLIFE 2020 (ML2020) restoration sites.
- An estimate of the impact of surface bunding on the carbon and greenhouse gas budgets.

The approach was to use the Durham Carbon Model and apply it to each of the monitored sites and restored areas assuming both pre- and post-restoration conditions.

These are the findings from Phase 3 and should be read alongside those from Phases 1 and 2.

- The average immediate effect of restoration was a benefit of 9.3 tonnes C/km^2/yr or 33.8 tonnes CO_{2eq}/km^2/y
- The overall immediate effect was a benefit of 1111 tonnes C/yr or 2629 tonnes CO_{2eq}/yr
- The modelling did suggest a benefit to bunding of 5 tonnes C/km^2/yr or 33 tonnes CO_{2eq}/km^2/yr.
- The overall restoration provided only negligible additional resilience.
- The GHG benefit of restoration accelerated over time.
- The accumulated benefit by 2080 was £1.6 million at net present value.

We recommend:

- Use of enhanced carbon sequestration techniques to provide greater value – these could include use of local biochar or methane suppression.

Contents

1. INTRODUCTION

This report covers Phase 3 of the modelling of MoorLIFE2020, and most of the set-up of the work was common with Phase 1 and 2. Phase 3 uses a different approach to understanding the impact of restoration upon Carbon (C) and Greenhouse gas (GHG) budgets so as to remove some of the problem of vegetation attribution identified in previous work.

Within the terrestrial biosphere, the northern peatlands are the most important terrestrial C store (Yu et al, 2014; Loisel et al., 2014). Despite only covering ~3% of Earth's total land area (Rydin and Jeghum, 2015), peatlands store 33% of the global terrestrial C. Though estimates vary depending on methods used (see reviews of Yu, 2012; and Loisel et al, 2017; for further discussion), it is estimated that 500 ± 100 Gtonnes C is stored in northern peatlands (Gorham, 1991; Yu et al, 2014; Loisel et al., 2014), which is approximately equivalent to the total C attributed to terrestrial vegetation (IPCC, 2013), or the cumulative anthropogenic CO_2 emissions from fossil fuels, industry and land use change activities for the period 1870 – 2015 (Le Quere et al., 2016). Peatlands in the UK represent less than 1% of the 3.5 million km^2 of the northern peatlands that mainly occupy the boreal and subarctic zones (Gorham 1991); however, UK blanket peats represent around 10-15% of the world's blanket peat resource (Tallis 1997). The JNCC (JNCC, 2011) concluded there were 17,125 km^2 of deep intact peat in the UK.

The very existence of peatlands depends upon the fate of organic matter, and the estimation of C budgets of peatlands has been a common research target. Initial approaches to C budgeting for peatlands were to measure the long-term accumulation rate by dating the depth profile (e.g. Turetsky et al., 2004). However, this approach must assume accumulation and cannot account for short periods of net loss, nor can it estimate the species of carbon. It is vital to know the species of carbon that are being lost, because carbon from a peatland can be lost to the atmosphere as carbon dioxide (CO_2) or as the yet more powerful greenhouse gas, methane (CH_4) (Houghton et al., 1995). Furthermore, carbon from peatlands can be released into water as dissolved or particulate forms: dissolved organic carbon (DOC) and particulate organic carbon (POC). As an alternative approach, it is possible to consider the carbon budget as the sum of measurements of the ongoing fluxes of all carbon species into and out of the peat ecosystem, and complete contemporary carbon budgets of peatlands are now common (e.g. Worrall et al., 2003, Billett et al., 2004, Roulet et al., 2007, Nilsson et al., 2008).

Many areas of northern peatlands have been subjected to a range of historical and current environmental and anthropogenic pressures, such as climate change, drainage, fire, peat extraction, and land-use change. These drivers of change may impact carbon cycling processes, potentially leading to positive feedback mechanisms, in turn leading to enhancement of atmospheric radiative forcing (e.g. Petrescu et al., 2015) and to the peatlands becoming net sources of GHG to the atmosphere. But the very fact that peatlands have become net sources to the atmosphere as a result of human activity means that there is an opportunity to attempt a reversal of their impacts and restore peatlands with the hope of creating sinks of greenhouse gases.

The purpose of this project is to assess the carbon and GHG benefits of restoration works undertaken by Moors for the Future Partnership (MFFP) as part of the MoorLIFE 2020 project.

2. AIMS & OBJECTIVES

The aim of this phase was to quantify the GHG benefits of the restoration works conducted under the MoorLIFE 2020 project; more specifically the project will:

i) Develop a look-up table approach to understand the carbon and greenhouse gas exports and budgets for use on the peatlands of the South Pennine Moors Special Area of Conservation and Peak District National Park.

ii) Apply the look-up table approach to the MoorLIFE 2020 restoration, specifically:
   a. Calculate the GHG budget of the restored areas compared to unrestored areas with the aim of producing the emissions factor for the restoration works. The GHG budget will account for avoided loss as well as temporary and perpetual gains.
   b. Evaluate the longer term (50 – 100 Years) potential to increase, reinstate and protect the ecosystem service of net carbon sequestration and climate change mitigation.
   c. Assess the economic value of the restoration over the longer term.

iii) Estimate the impact of surface bunding on the carbon and greenhouse gas budgets.

These specific objectives of Phase 3 arose out of the Phase 2 of work where the analysis showed some unsuspected results:

- the average immediate effect of restoration was a disbenefit of 4.0 tonnes C/km^2/yr or 14 tonnes CO_{2eq}/km^2/y;
- the overall immediate effect was a disbenefit of 99 tonnes C/yr or 364 tonnes CO_{2eq}/yr;
- the restoration achieved carbon and GHG benefit in 48% of the restoration areas; and
- the restoration provided no measurable additional resilience.

It was suspected that the results of Phase 2 of the project were dominated by uncertainty in vegetation attribution. Specifically: this second phase of the study has highlighted the uncertainty in model results due to assignment of vegetation that arises from it being impractical to measure and monitor vegetation at each restoration site and assigning each restoration site to a monitored site. In the previous phases of the work each restoration site was assigned to a particular monitoring site and assumed to have the vegetation of that monitoring site, whether or not the restoration activity was inconsistent with the vegetation on the montoring site assigned to it.

Therefore, we proposed a look-up table approach be used to pre-generate predictions for the range of possible combinations that would be relevant to the setting such that when values are required for an area and a restoration method then that result already exists. In this manner, the problem of attribution does not exist as the proposed combination for any restoration has already been calculated and no reference to a monitoring site was required.

3. Project Deliverables

Over all the phases of the project we will deliver:

- An estimate of the current greenhouse gas emissions of the MoorLIFE2020 project areas
- An estimate of the amount of greenhouse gas emissions saved by the restoration works
- Recommendations on means of optimising the greenhouse gas emissions from the area
- A projection of the long-term (decadal) behaviour of the sites and their potential to reach and sustain ecosystem service targets
- An assessment of the economic value of the greenhouse gas that has, that is and that could be saved from the moors.

4. Approach and Methodology

Our approach has been based upon the use of the Durham Carbon Model with projections in to the future under climate change. The modelling includes and compares pre- and post-restoration scenarios. The study does not include the emissions from the physical works, but these could be assessed relative to standard values (Worrall and Clay, 2014) and have been assessed in a separate report (Titterton et al., 2022).

4.1. The Durham Carbon Model

This was based upon the application of the Durham Carbon Model (DCM – Worrall et al., 2009). Details of the DCM have been given in the Phase 2 report and will not be repeated here.

Model development and calibration – Monitored sites

The DCM has previously been run for the Peak District National Park as part of a Defra project into provision of ecosystem services (Defra, 2009). The DCM for the MoorLIFE 2020 restoration sites was calibrated using water table observations for the monitored sites (Table 1).

Table 1. The Site names and Treatment units of the MoorLIFE 2020 monitored sites.

Site name	Treatment unit	Area (ha)	Altitude (m-asl)
Birchinlee	Eriophorum – Control	0.9	490
	Eriophorum – Sphagnum	0.9	490
Derwent & Howden	Calluna – Control	0.74	495
	Calluna – Sphagnum	0.59	495
	Calluna – Sphagnum + gully blocking	0.48	495
Featherbed Moss	Reference (Penguins Drift)	0.71	505
Moss Moor	Molinia – Control	1.2	385
	Molinia – Sphagnum	1.2	385
Kinder	Firmin – Control	0.63	622
	Nogson – Sphagnum + gully-blocking	0.69	622
	Olaf – Vegetation	0.48	622

Develop a look-up table approach

The look-up table was generated using the Durham Carbon Model (DCM). The DCM runs on a series of inputs and any reasonable combination of these can be considered. The ranges and combinations were agreed with MFFP staff, and the combinations agreed were:

- Altitude – the altitude range was set between 200 and 650 m above sea level
- Grazing – set as a Yes/No option
- Grazing intensity – when grazing is selected then the grazing intensity can be set to range between 0.1 and 0.5 ewes/ha
- Managed burning – no managed burning was included
- Peat area – set to 100%
- Bare soil area – this would set to range between 1 and 15%.
- Drainage – as for grazing, this is first set as a Yes/No option
- Drainage spacing – spacings between 0 and 25 m were used. After 25 m spacing the impact of the drains is no more than natural stream network.
- Gullies – set to Yes/No
- Vegetation – to include: forest, grass; heather; sedge and sphagnum. The percentage cover of each was set to be between 0 and 100%.

The factorial combination of all these inputs led to 1.2 million possible model runs and this was thought impractical. So of the 1.2 million possible combinations, a random set of 250,000 was selected which, when illogical combinations were removed, amounted to 230,000 combinations. Illogical combinations were those where vegetation cover added up to more than 100%. The 230,000 combinations were divided between those with and without gullies as it is not possible to model drains as well as gullies on the same piece of ground. The DCM was then run for all 230,000 combinations and results automated through a pivot table and visual basic macros within Excel2016.

Model application

The look up table was applied across all restored areas (Table 2) and the calibrated model was applied in two scenarios, pre- and post-restoration.

Table 2. Features of the MoorLIFE2020 restored areas, where "Monitoring site" represents an equivalent vegetation type identified from the list of monitoring sites (see Table 1) and for which the model had previously been parameterised and calibrated (D&H = Derwent and Howden). The altitude range used in the modelling wherever a range was used and the restoration methods considered, where Sphag. = Sphagnum planting; Brash = heather brashing; GB = gully blocking; HC = heather cutting; R.removal = Rhododendron removal; CC = conifer cutting; Erio. = Eriophorum planting; and LSF = lime, seed and fertiliser.

Restored area	Monitoring site	Area (ha)	Altitude range (m asl)		Restoration method		
Alport	Firmin	90	483	464	Sphag.	Brash	GB
Arnfield	D & H	15	299	476	HC		GB
Arnfield	D & H	58	299	476	Sphag		GB
Arnfield	Birchinlee	379	299	476	R.removal		
Ashop	D & H	14	468		HC		
Ashop	D & H		322	432	HC		
Ashop	D & H		474	483	HC		GB
Ashop	D & H	52	468		Sphag.		
Ashop	D & H	85	474	514	Sphag.	CC	GB
Ashway	Birchenlee	118	426	496	Sphag.	HC	GB
Ashway	Birchenlee	624	426	496	R.removal		
Birchenlee	Birchenlee	30	459	463	Brash		GB
Birchenlee	Birchenlee	129	289	458	Sphag.		GB
Black Moss	Birchenlee	1.9			Sphag.		
Bradfield	D & H	51.4	393	447	Sphag.		
Butterley	Moss Moor	33			R.removal		
Castleshaw	Moss Moor	37	324	394	Sphag.	Erio.	GB
Close Moss	Moss Moor	51	321	465	Sphag.		
Close Moss	Moss Moor	1035	321	465	Sphag.		
Crowden	D & H	16	473		Sphag.		
Crowden	Moss Moor	2	472		Sphag.		
Crowden	Moss Moor	4	470		Sphag.		
Crowden	Moss Moor	10	472		Sphag.		
Crowden	Moss Moor	14	435		Sphag.		
Crowden	Moss Moor	38	431	457	Sphag.		
Crowden	Moss Moor	11	470		Sphag.		
Crowden	Moss Moor	30	335	375	Sphag.		
Crowden	Moss Moor	23	311	359	Sphag.		
Crowden	Moss Moor	14	452	472	Sphag.		
Crowden	Moss Moor	11	379	444	Sphag.		
Crowden	Moss Moor	12			Sphag.		
Crowden	Moss Moor	13	388	457	HC		
Crowden	Moss Moor	10	472		R.removal		
Crowden	Moss Moor	74	375	439	R.removal		GB
Deanhead	Olaf	12			Sphag.	Erio.	GB
D & H	D & H	118	434	454	Brash	CC	GB
D & H	D & H	29	447		Sphag.		
D & H	D & H	99	319	471	R.removal		
D & H	D & H	53	480		Sphag.		
D & H	D & H	20	457		Sphag.		
D & H	D & H	39	489	490	HC		GB
D & H	D & H	39	316	446	HC		GB
East Crowden	Olaf	20	516		Sphag.		GB
Heptonstall	Moss Moor	151	297	448	Sphag.	R.removal	GB
High Brown	Firmin	38			LSF		
Keighley	D & H	102	310	317	Sphag.	HC	
Marsden	D & H	32	272	468	Sphag.	HC	Brash
Marsden	D & H	1275	272	468	R.removal		
Midgley	D & H	96	331	355	Sphag.	Brash	GB
Nether Moor	D & H	59	282	444	Sphag.	HC	
Oxenhope	Olaf	168	306	401	Sphag.	Brash	GB
Peaknaze	Firmin	46	373	473	Sphag.	Brash	GB
Pikenaze	Moss Moor	171	440	452	Sphag.	MC	
Readycon	Birchenlee	43	349	443	Sphag.	Brash	MC
Ronksley	D & H	15	316	458	HC		GB
Ronksley	D & H	98	453	457	Sphag.		GB
Saddleworth	Olaf	51	473	475	Sphag.		
Snailsden	D & H	4	383	393	Sphag.	HC	
Soyland	Olaf	46	314	343	Sphag.	Brash	GB
Stalybridge	Firmin	32	477	486	Brash	LSF	
Thornton Moor	D & H	0.4	320	339	Sphag.	Brash	
Trawden	Birchinlee	7	462	465	Sphag.		
Ughill	D & H	0.2	317		Sphag.		
Warley Moss	Birchinlee	44	376	421	Sphag.	Brash	HC
Wessenden	Olaf	95	373	464	Sphag.		
Wessenden	Olaf	188	373	464	R.removal		
Widdop	Moss Moor	13	304	420	Sphag.		
Widdop	Moss Moor	12	304	420	Sphag.		
Widdop	Moss Moor	14	304	420	Sphag.		

The details of how each restoration method was modelled was described in the report Phase 2 and is not repeated here.

Future projection
The new results were projected forward under a climate change scenario. The climate scenario chosen was the Alb scenario of UKCP2009 for 2010 to 2080 in decade time steps (Murphy et al., 2009). The UKCP2009 predicts that by the 2080s the mean summer temperature across the UK will have risen by 3.6 °C and mean winter temperatures across the UK will have risen by 2.8 °C. The decade climate projections were used with two scenarios – a pre- and post-restoration scenario. The results from these scenarios were accumulated and the differences between them examined. It did not prove necessary to project results for centuries as important transitions were observed within decades.

Transitionary sinks
Transitionary sinks are sinks that occur between two states, for example a gully infills after blocking – the gully does not go on filling and so the sink is temporary or transitionary. Transitionary sinks were not re-calculated as part of this phase of the project and so those reported below as those from Phase 1 and Phase 2 reports.

4.2. Estimation of the economic value of carbon sequestration
Crucial to the deliverables of this work package is, firstly, the choice and application of the model scenarios and projections; and secondly the scheme of funding for carbon benefits (carbon credits). The model scenarios have been chosen so as to provide the evidence required. The greenhouse gas emissions from a restored area must be judged in the light of the phenomena of triple win, i.e. a restored area can be saving greenhouse gases because of: avoided loss, transition gain or a perpetual sink.

A fully-functioning restored area is hopefully a sink of GHG as the peat soil grows, although it should always be noted that a net sink of carbon does not necessarily mean a net sink of GHG. This difference between the carbon and GHG budgets is due to the different greenhouse gas warming potential of the different forms of release, for example, the different greenhouse gas warming potential of CO_2 and CH_4. The potential for triple win was inherent in the DCM development as described in Worrall et al. (2009) and inherent in the concept of triple win is the understanding of the emissions from the counterfactual state, i.e. the difference between current restored state and what the state would have been had no intervention happened. Any avoided loss is counted for by comparing the pre- and post-restoration scenarios, but this would not include any transitionary sinks. The benefit of transitionary gains will be assessed separately.

Carbon credits
The development of the Peatland Code in 2013 (IUCN, 2017) has made it possible for schemes to register and claim the greenhouse gas benefit they provide as part of funding restoration. The Peatland Code recognised, or perhaps limited itself, to transitions between six categories, listed here in order of increasing GHG sink size: actively eroding: hagg/gully; actively eroding: flat bare; drained: artificial; drained: hagg/gully; modified; and near natural. In its designation of categories and assignment of emission factors The Peatland Code sensibly emphasised the best known transitions (e.g. revegetation of bare peat) and the one that could always be considered the no regrets strategy.. We then applied the traded carbon price as outlined in BEIS (2018a) and the non-traded carbon price as outlined in BEIS (2018b). The non-traded value estimates the total value of the GHG stored and as such tries to include the societal benefits of the carbon stored and not just the value it could be sold at.

4.3. Impact of bunding
Bunding has been employed as an alternative approach to raising water tables on Close Moss. To model the impact on C and GHG budgets the change in water table recorded across the bunds was assessed relative to control and interpreted as a fraction of the water table on the control. In the

initial case this was taken as having a water table 14% higher. The DCM was then run for Close Moss given this assumption.

5. Results

A number of results stand from the Phase 2 report: the calibration against water table depth; and the carbon and greenhouse gas budgets of the monitoring sites based on the 2021 vegetation survey.

5.1. Look up table approach

The look up table developed and used in this Phase 3 has been supplied separately and an example screenshot is shown below (Figure 1). Example summary results are contained within Appendix 1.

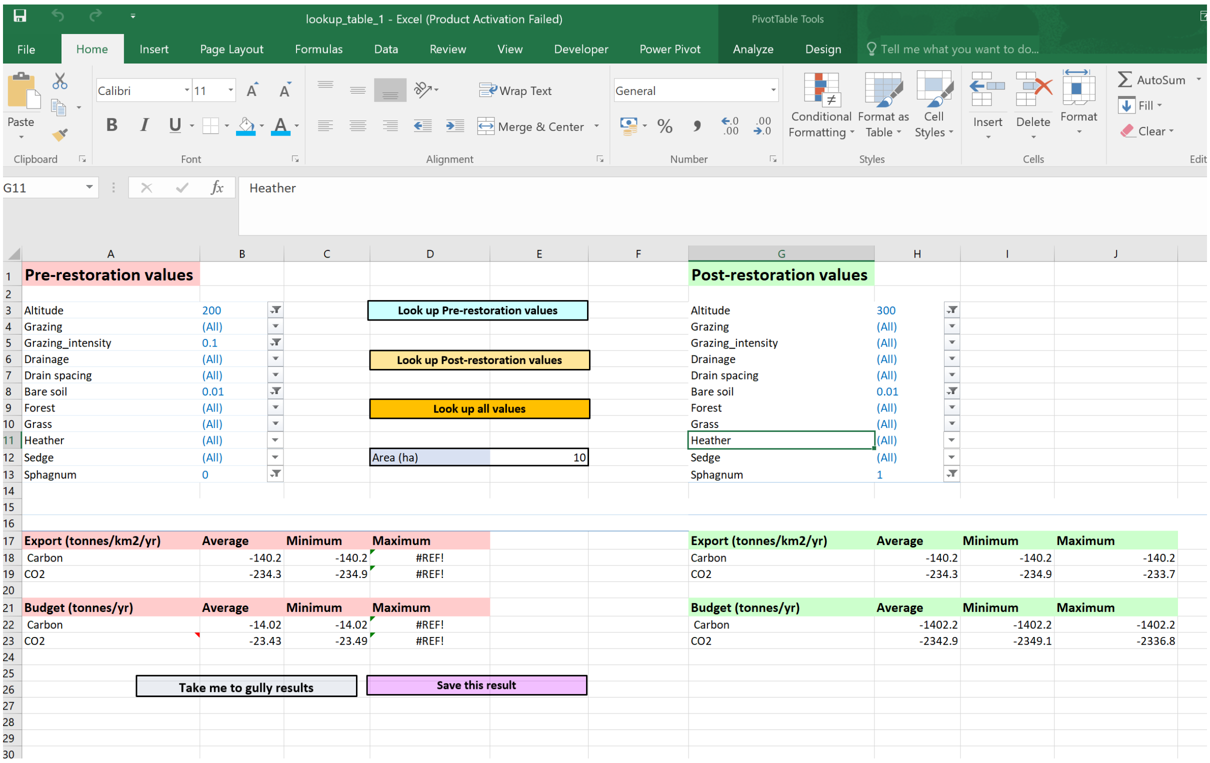

Figure 1. Screenshot of the look up model used and supplied in this study.

5.2. Carbon and Greenhouse gas budgets

The immediate benefit of restoration

Based upon the 2020 vegetation survey, the average improvement on the C export of the restored sites compared to their pre-restoration C export was 5.4 tonnes C/km^2/yr; of the 69 areas that could be modelled, 61 were predicted to have a net benefit with respect to their C export, but 8 were predicted to have experienced no net benefit (Figure 2). The average improvement on the GHG export of the restored sites compared to their pre-restoration CO_2 export was 28 tonnes CO_{2eq}/km^2/yr. Of the 69 areas that could be modelled, 60 were predicted to have a net benefit with respect to their GHG export, but 9 were predicted to have experienced no net benefit (Figure 3). All of the 9 areas that showed no benefit were areas where only heather-cutting (and no other interventions) had taken place.

Results based on the 2021 vegetation survey, and based on the look up approach, predicted that 97% of restoration sites showed an immediate benefit of restoration (Figure 4). Furthermore, the average impact of restoration was a benefit of 9.2 tonnes C/km^2/yr or 33.8 tonnes CO_{2eq}/km^2/yr. Overall the immediate effect was a benefit of 1,111 tonnes C/yr or 2,629 tonnes CO_{2eq}/yr. From the modelling based upon the 2020 vegetation the greatest improvement was for sites where there was gully-blocking coupled with sphagnum planting. For the results based on the 2021 vegetation survey, however, the greatest improvement was for sites with sphagnum planting and gully-blocking.

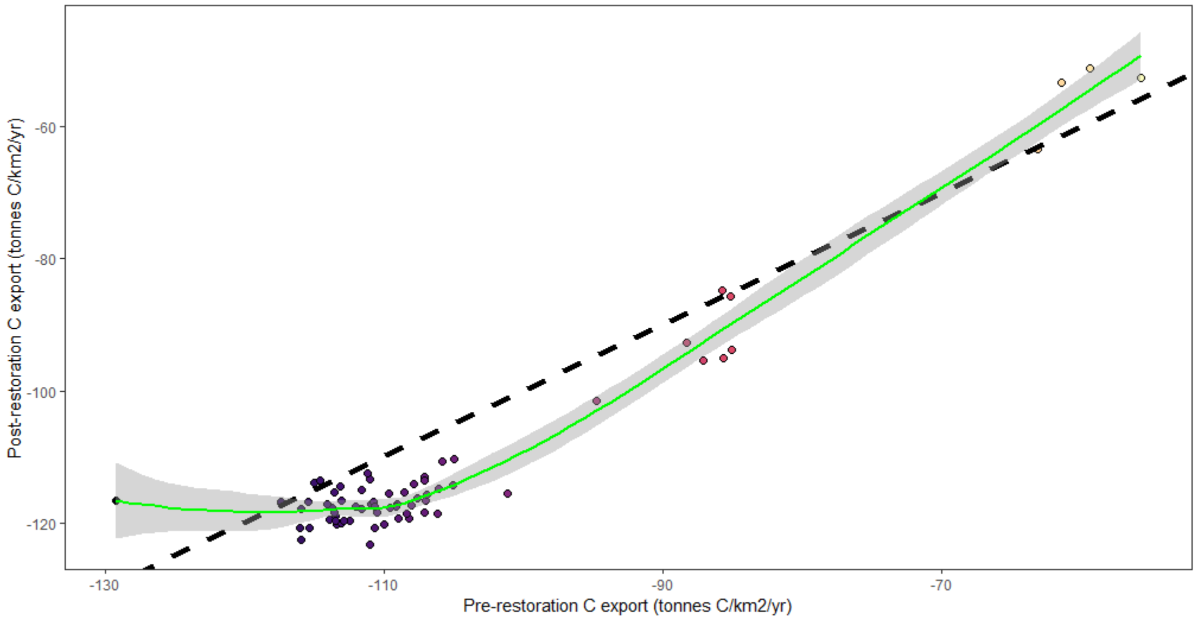

Figure 2. Comparison of pre-restoration C export with the post-restoration C export based upon the 2020 vegetation survey. The dashed line (—) is the 1:1 line and the green line is the LOESS (locally estimated scatterplot smoothing) line with its standard error shaded.

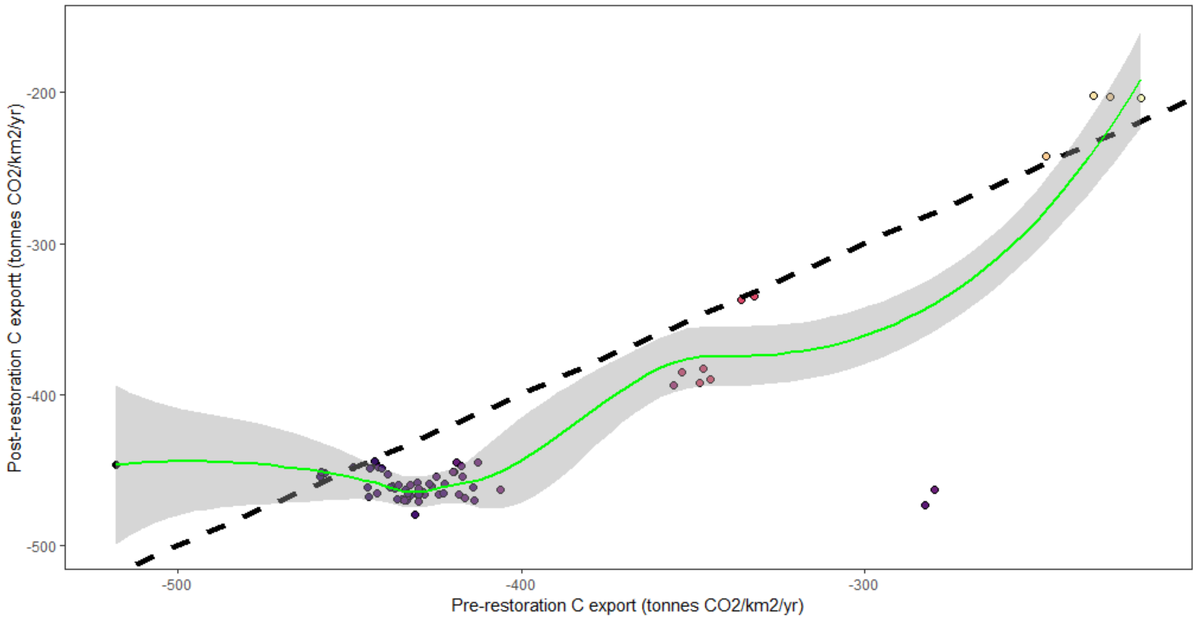

Figure 3. Comparison of Pre-restoration CO_2 export with the Post-restoration CO_2 export based upon the 2020 vegetation survey. The dashed line (—) is the 1:1 line and the green line is the LOESS (locally estimated scatterplot smoothing) line with its standard error shaded.

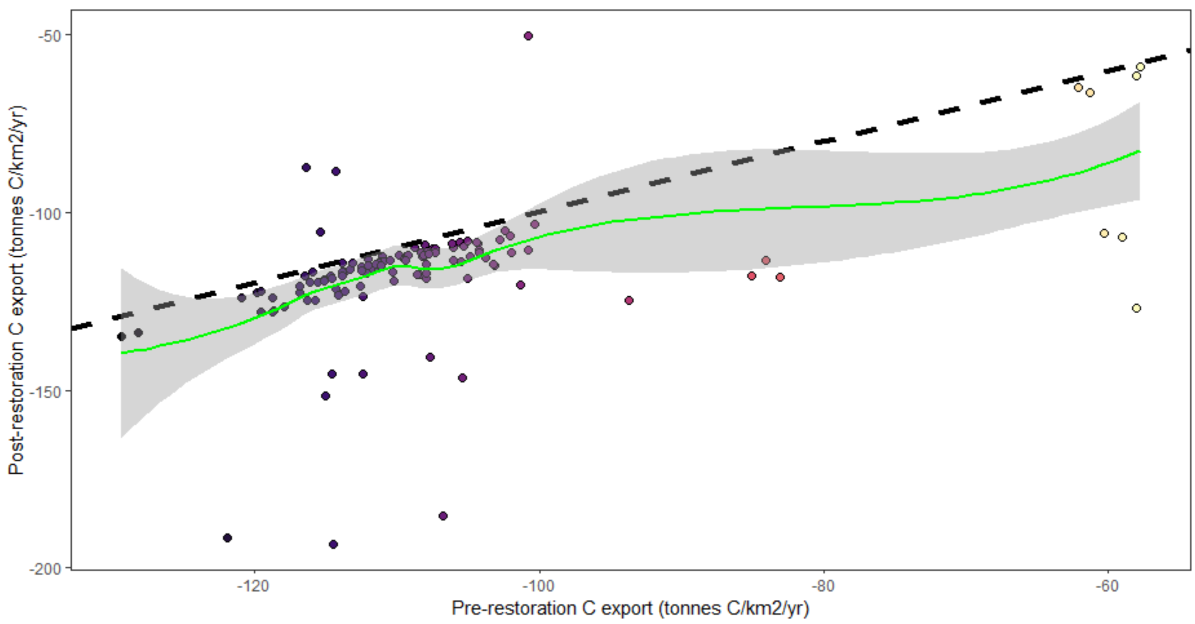

Figure 4. Comparison of Pre-restoration C export with the Post-restoration C export based upon the 2021 vegetation survey and the 2022 remodelling. The dashed line (—) is the 1:1 line and the green line is the LOESS (locally estimated scatterplot smoothing) line with its standard error shaded.

The distribution of the CO_2 export benefit shows a distribution centred on the average benefit (Figure 5): the sites with the lowest benefit and/or greatest disbenefit were high altitude sites. As with the Phase I report no relationship with altitude was found – rather that greatest benefit was achieved where gully-blocking and sphagnum planting were implanted together.

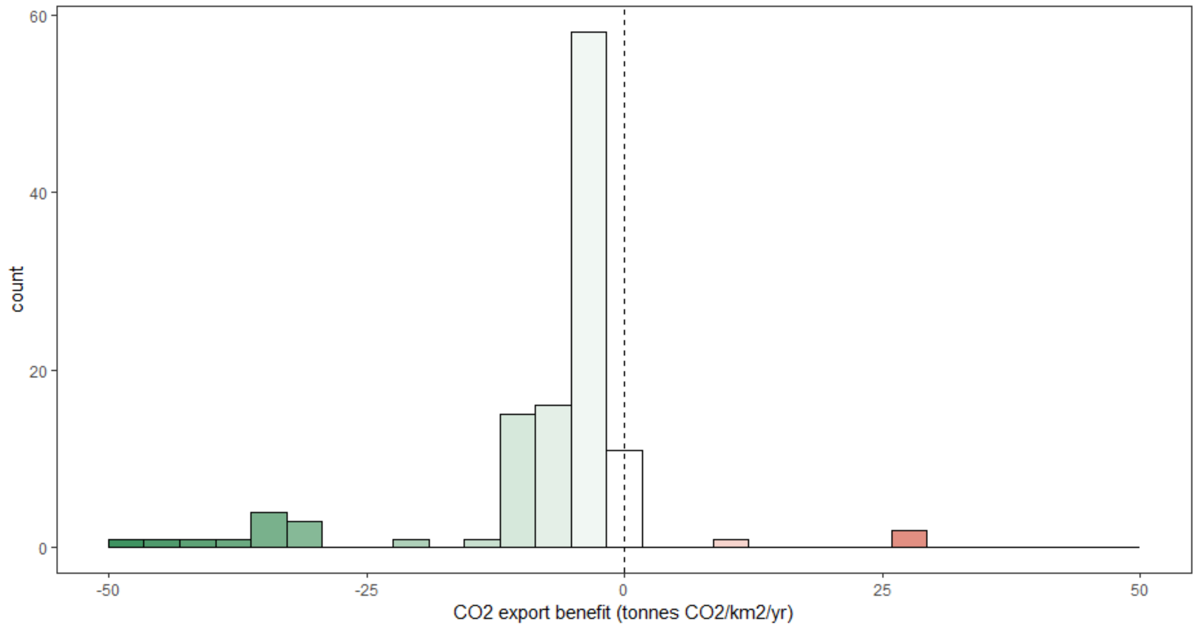

Figure 5. The distribution of the CO_2 export benefit, i.e. the difference between the pre- and post-restoration scenarios, based upon the 2021 vegetation survey.

The new restoration areas (restored in 2021) were considered separately and the results given in Table 3 and show that sphagnum planting was the key to a restoration benefit while grass planting seems to have a disbenefit.

Table 3. The carbon and GHG budget of the restored areas (restored in 2021) and based on the 2021 vegetation surveys. The benefit is given as positive value when restoration has been beneficial. Where X is ether C or CO_{2eq}.

Restored area	*Treatment*	*Export (tonnes X/km²/yr)*					
		Pre		*Post*		*Benefit*	
		C	*CO_{2eq}*	*C*	*CO_{2eq}*	*C*	*CO_{2eq}*
Arnfield	*Gully-blocking*	*-50*	*-193*	*-48*	*-185*	*-2*	*-8*
Crowden	*Grass planting*	*-78*	*-305*	*-69*	*-282*	*-9*	*-23*
Cupwith	*Sphagnum planting*	*-39*	*-144*	*-77*	*-284*	*+38*	*+140*
Pikenaze	*Sphagnum planting & Molinia cutting*	*-43*	*-174*	*-63*	*-256*	*+20*	*+82*
Twizle Head	*Gully-blocking*	*-66*	*-265*	*-65*	*-256*	*-1*	*-9*
Twizle Head	*Sphagnum planting*	*-45*	*–176*	*-66*	*-260*	*+22*	*+84*

Transitionary gains

The infilling of gullies would represent an additional C sink of 28 tonnes C/yr across a period of up to 25 years, but the uncertainty on this estimate is large with the inter-quartile range of 10 to 55 tonnes C/yr. In turn this equates to an additional CO_2 sink of between 27 and 200 Tonnes CO_{2eq}/yr with a median of 77 tonnes CO_{2eq}/yr.

5.3. Future projections

The future predictions for the C exports, for the restored areas, are shown below (Figure 6). Both the C and CO_2 budgets show that transitions from net sinks to net sources are typically not until the 2080s. Over time the proportion of the restored areas that are sources match between the projected restoration and counter-factual case (Table 4). For the period between 2060 and 2070 the proportion of restored areas that are sources shows that the counter-factual case actually does somewhat better by this particular measure than the post-restoration case. However, this measure (in Table 4) is simply a binary assessment of sink or source rather than magnitude of the export or the budget for the size restoration area. Concerning the latter scenario, the period prior to 2050 seems to show a period of more rapid decline in sink size compared to period after 2050 – this must be a manifestation of the particular climate projection. Note that the change between sink/source status was not affected by going over to estimates based upon the look-up table approach.

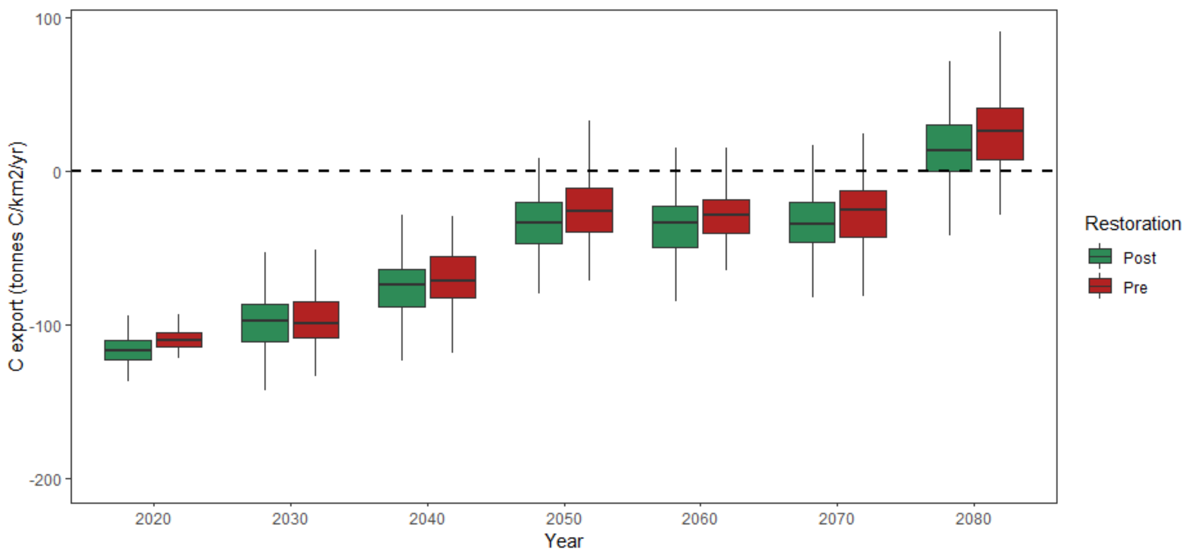

Figure 6. The C export of each restored area, for both pre- and post-restoration scenarios, projected forward under UKCP2009 scenario A1b.

Table 4. The proportion of restored areas projected to be a net source at each time step. There are 68 projected areas and results are given for both C and CO_2 export.

	Restoration	2020	2030	2040	2050	2060	2070	2080
C	Pre	79	79	79	72	75	73	9
	Post	79	79	79	72	69	67	13
CO_2	Pre	89	89	89	81	77	76	13
	Post	89	89	89	81	85	81	9

Results given in Figure 6 are for the CO_2 export for each of the restored areas, but what are the results over the whole area restored as part of the MoorLIFE 2020 project? As climate changes, the peat soils warm which increases soil CO_2 respiration but also causes the depth to the water table to increase and so leads to decreases in the CH_4 flux. For the C budget the flux of CH_4 makes a small component in comparison to the soil CO_2 respiration, therefore, change in the C budget is dominated by the changes in soil respiration. Conversely, for the GHG budget the comparatively larger greenhouse gas warming potential of CH_4 means that the decrease in CH_4 flux makes a comparatively large component of the CO_2 budget. The results for the whole MoorLIFE 2020 working area show that for the C budget (Figure 7) it matters little whether restoration has occurred or not in that under the pre-restoration scenario the restoration areas will become net sources of C by 2076, while for the post-restoration scenario the transition is projected to be 2077. However, the GHG saving due to restoration does continue to grow (Figure 8) – for the total CO_2 budget the time series is actually diverging over time and so the benefit of the restoration is accelerating (Figure 9). For the pre-restoration scenario we predict the areas would become a net source by 2092, but for the post-restoration scenario that transition would not occur until after 2100. We can hypothesise that the ongoing accelerating CO_2 benefit compared to the C benefit is due to contrasting impacts of climate change on the respective flux components.

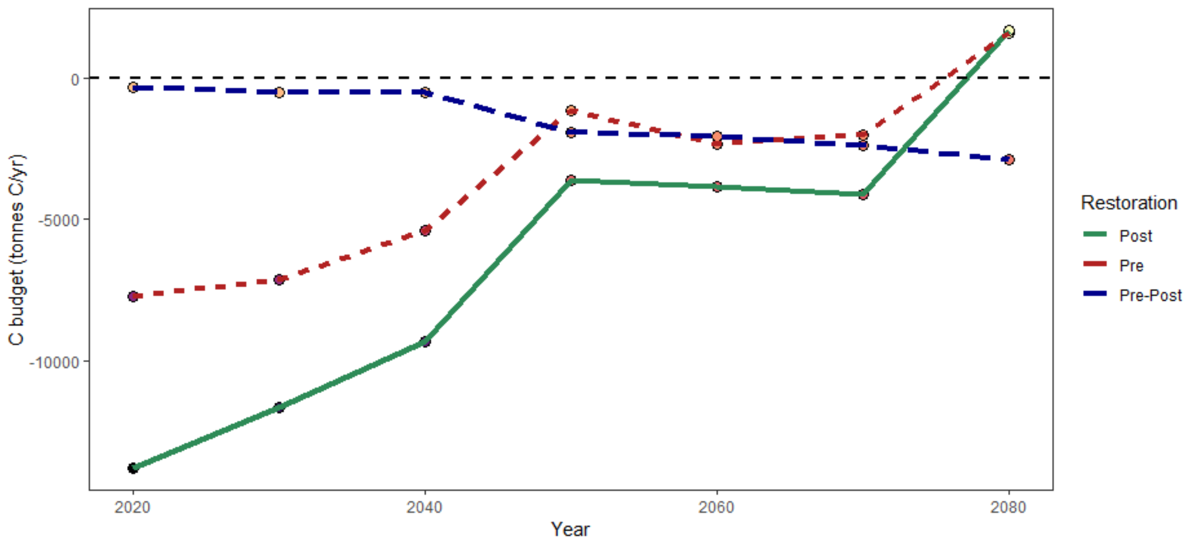

Figure 7. The time series of the total C budget for all MoorLIFE 2020 restored areas comparing the pre- and post-restoration projected forward under UKCP2009 scenario A1b. The Pre-Post scenario represents the difference between time course of the C budget from the Pre and Post scenarios. Based upon results of 2021 vegetation surveys.

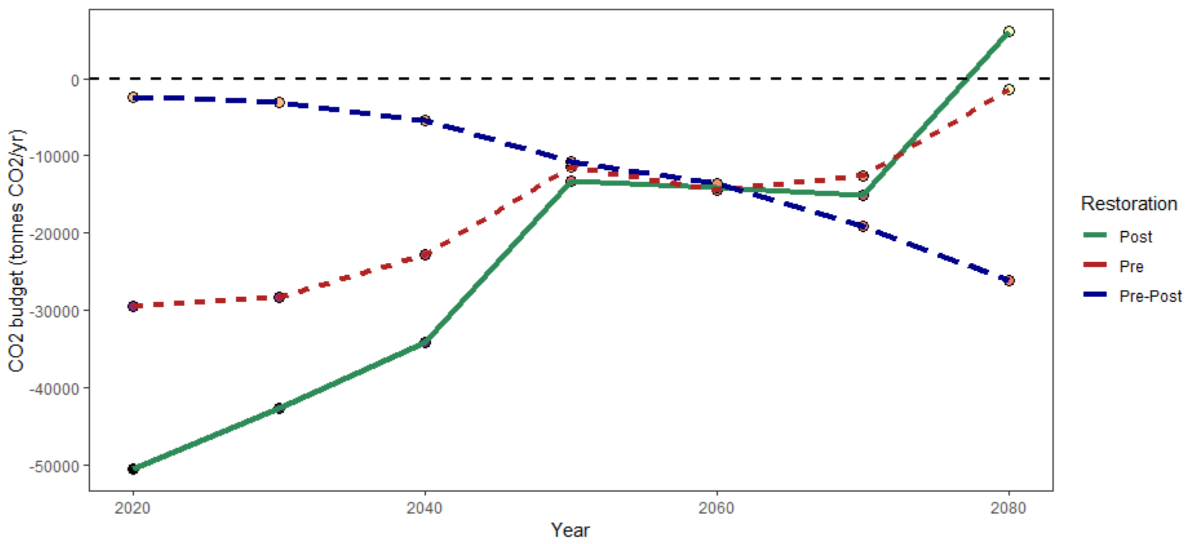

Figure 8. The time series of the total CO_2 budget for all MoorLIFE 2020 restored areas comparing the pre= and post-restoration projected forward under UKCP2009 scenario A1b. The Pre-Post scenario represents the difference between time course of the C budget from the Pre and Post scenarios. Based upon results from 2021 vegetation survey.

Transitionary sinks

As from the Phase 2 report, the infilling of gullies would represent an additional C sink of 28 tonnes C/yr across a period of up to 25 years, but the uncertainty on this estimate is large with the inter-quartile range of 10 to 55 tonnes C/yr. In turn this equates to an additional CO_2 sink of between 27 and 200 Tonnes CO_{2eq}/yr with a median of 77 tonnes CO_{2eq}/yr. The magnitude of the transitionary sink is not sufficient to make a difference to the results in Figures 4 and 5.

5.4 Economic value

Given the estimated accumulated GHG saving over the time since restoration it is possible to speculate on the value of the GHG saving. BEIS (2018a) give current and future values of traded carbon from 2017 to 2030 and they predict a steep rise in traded carbon value from the £4.13/tonnes CO_{2eq} in 2017 to £79.43 in 2030. In Figure 8, the accumulated value projected forward under the post-restoration management scenario shows that the improved GHG budget would accrue £72 million at tradeable value but £1.6 million at net present value at the tradeable value. No allowance for the cost of restoration is included in this calculation. Recent studies on the economics of peatland restoration include Glenk and Martin-Ortega (2018) and Gunther et al. (2018).

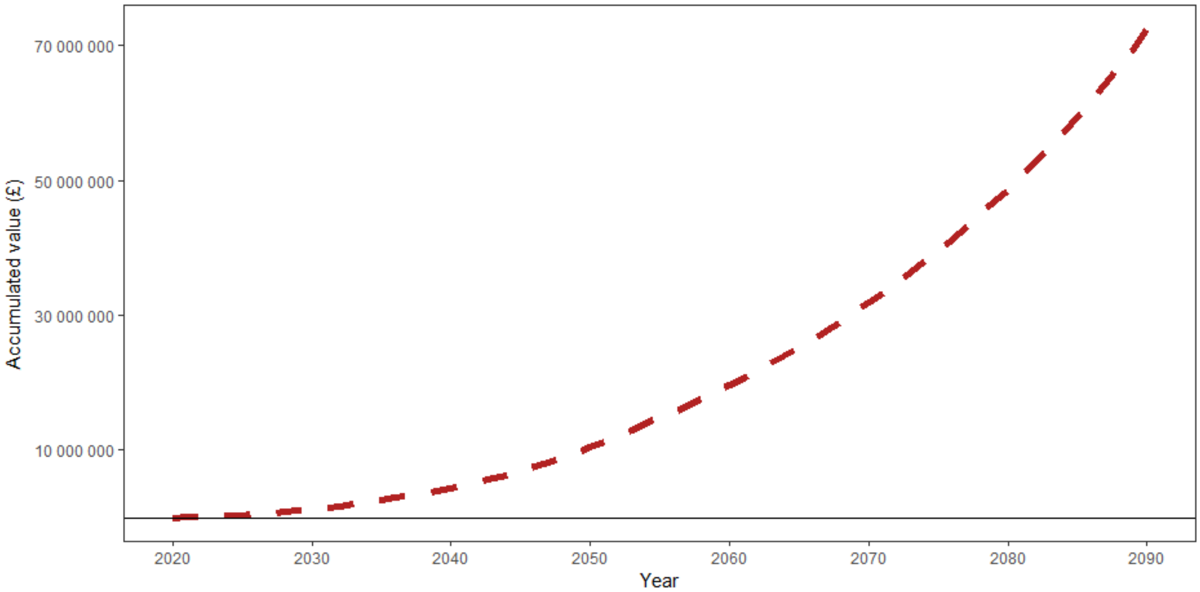

Figure 9. The accumulated value based on the tradeable carbon value (—), and the net present value (····): based on the 2021 vegetation survey data.

5.4. Impact of bunding

The DCM was run across the altitude range at Close Moss and the results (Table 5) do suggest that bunding would have a beneficial impact on C and GHG budgets.

Table 5. Comparison of C and GHG exports from across Close Moor with and without bunding.

	C (tonnes C/km²/yr)		GHG budget (tonnes CO_{2eq}/km²/yr)	
Altitude (m asl)	Without bunding	With bunding	Without bunding	With bunding
465	-97	-101	393	437
329	-109	-115	418	440
Benefit		-5		-33

6. CONCLUSIONS

- The restoration achieved carbon and GHG benefit in 96% of the restoration areas.
- The greatest impact was achieved for sphagnum planting and gully-blocking, while the restoration activity with the least impact was heather cutting.
- The average immediate effect of restoration was a benefit of 9.2 tonnes C/km^2/yr or 33.8 tonnes CO_{2eq}/km^2/yr.
- The modelling did suggest a benefit from bunding of 5 tonnes C/km^2/yr or 33 tonnes CO_{2eq}/km^2/yr.
- The overall and immediate benefit of restoration was 1,111 tonnes C/yr or 2,629 tonnes CO_{2eq}/yr in the first year after restoration.
- The restoration provided no measurable additional resilience. There were long term benefits in terms of GHG budgets but not in C budgets and so actual peat growth showed no additional resilience due to restoration.
- The GHG benefit of restoration accelerated over time.
- By 2080, the accumulated non-traded value of the saved GHG would be £72 million, however, when considered at net present value of the current-traded carbon price the value would be £1.6 million,
- A look-up table approach has been developed so that the modelling is not vulnerable to changes in the assignment of vegetation to sites.

7. RECOMMENDATIONS

7.1. *Enhanced greenhouse gas storage*

We recommend the exploration of enhanced carbon accumulation techniques, above and beyond sphagnum planting, to maximise carbon capture on sites, such as biochar infill for gullies, or methane sequestration.

7.2. *Remote monitoring*

There are a number of remotely-sensed products that could be used to monitor peat health. A number of examples have already been demonstrated to be useful for assessing peatland restoration. Worrall et al. (2022) used day and night land surface temperature, albedo and enhanced vegetation index (EVI) to demonstrate changes over restoration for the Thorne and Hatfield Moors. An example of the use of EVI for Bleaklow is shown in Figure 9. As an alternative approach it is possible to measure ground motion from satellite. Figure 10 shows the available ground motion data for part of the Bleaklow plateau and the surrounding area. The ground motion is given as annual average change since 2016 and suggests that the area around the Snake Pass has been subsiding (as is the common result for the UK). A *primo facie* interpretation of this type of data is that peat is degrading on the Plateau; however, this type of time series can reflect a number of processes – not only degradation/accumulation, for example, but a change in water table. Given the monitoring data already available for the MFF sites it would be possible to calibrate the Earth observation data to provide ongoing monitoring of restoration sites.

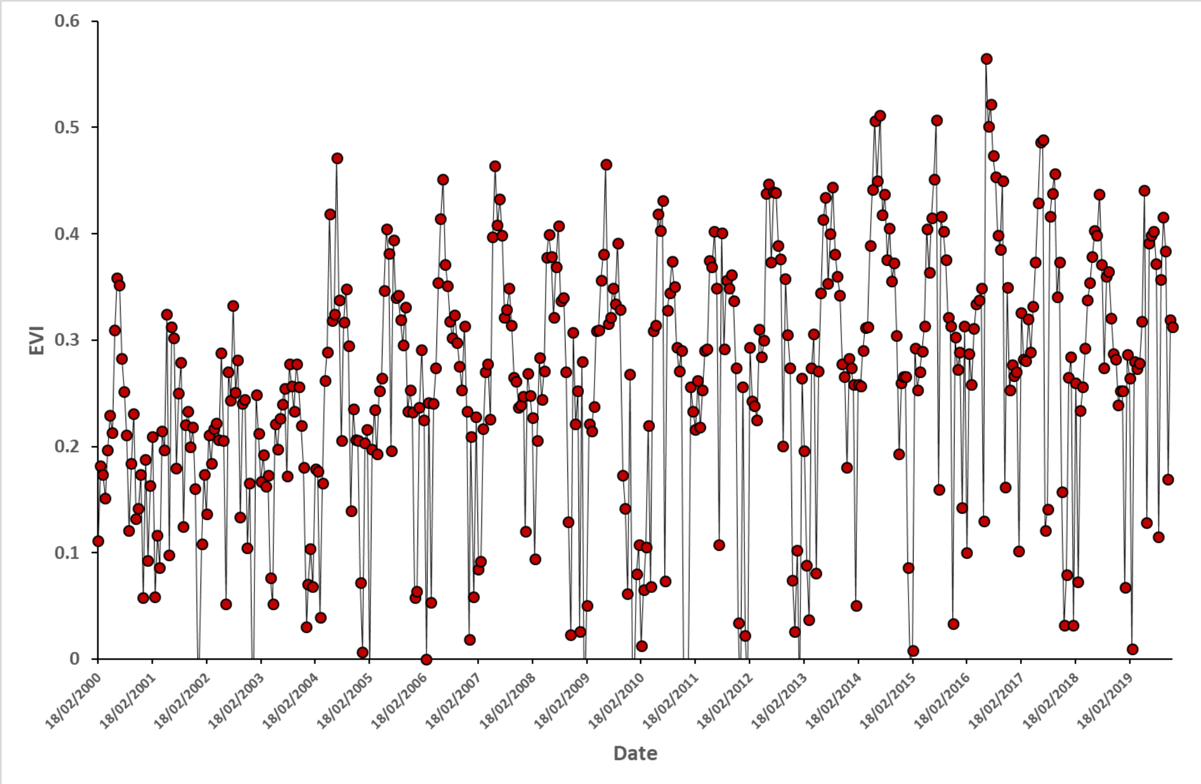

Figure 9. The time series of EVI (Enhanced Vegetation Index) on Bleaklow showing the two phases of restoration after the 2003 fire and after 2014.

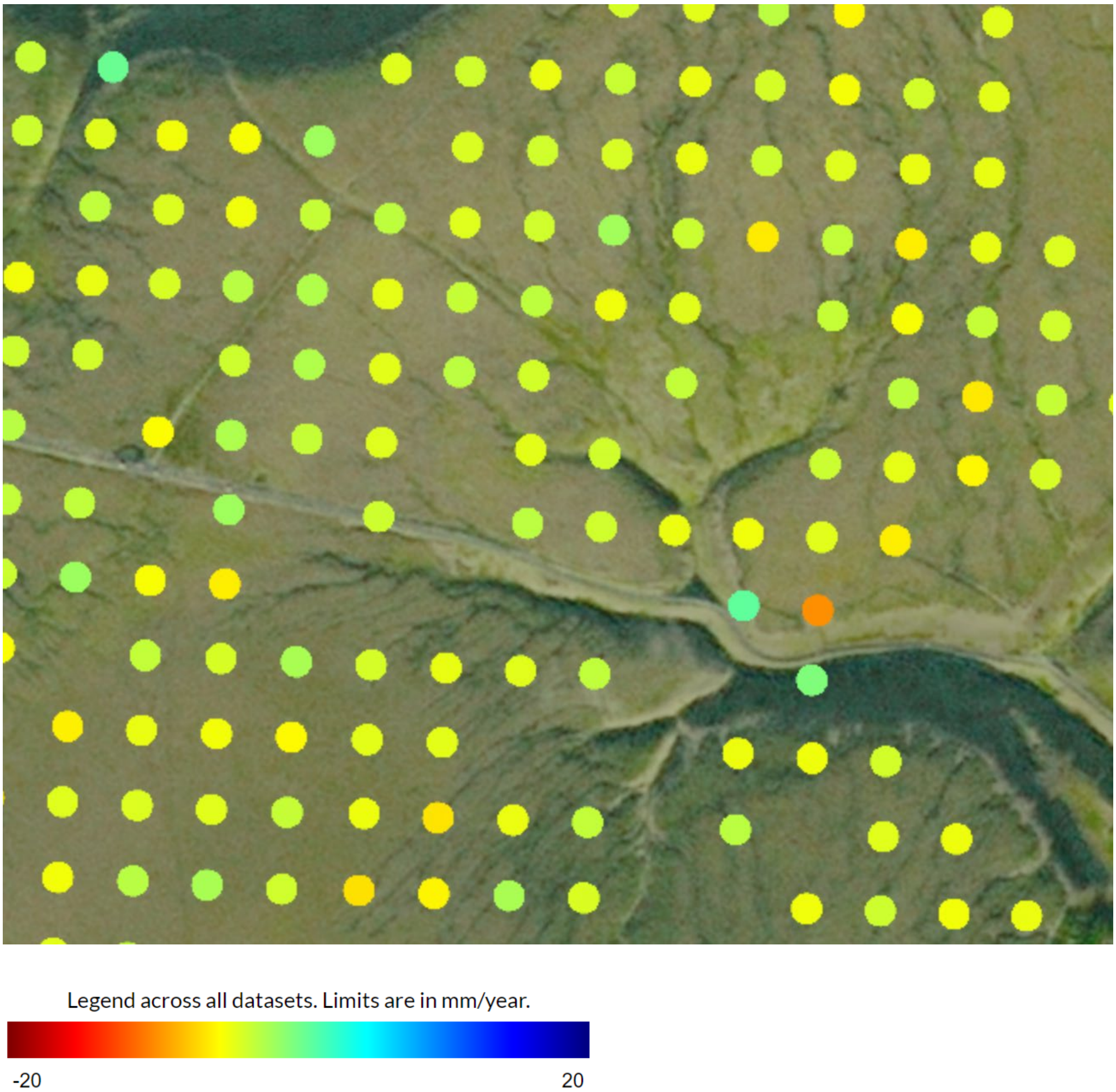

Figure 10. The ground motion across Snake's Pass including Doctor's Gate and Penguin's' Drift as measured from the Sentinel satellites.

References

BEIS (2018a). Updated short-term traded carbon values used for UK public policy appraisal. Department for Business, Energy & Industrial Strategy, London, UK.

BEIS (2018b). Valuation of energy use and greenhouse gas (GHG) emissions – Supplementary guidance to the HM Treasury Green Book on Appraisal and Evaluation in Central Government. Department for Business, Energy & Industrial Strategy, London, UK.

Billett, M.F., Palmer, S.M., Hope, D., Deacon, C., Storeton-West, R., Hargreaves, K.J., Flechard, C. and D.Fowler (2004), Linking land-atmosphere-stream carbon fluxes in a lowland peatland system. *Global Biogeochemical Cycles*, 18, 1, GB1024.

Clay, G.D. and F.Worrall. (2015). Estimating the oxidative ratio of UK peats and agricultural soils. *Soil Use & Management* 31, 1, 77–88.

Clay, G.D., Worrall, F., Plummer, R., and C.S.Moody (2018). Organic matter properties of Fennoscandian ecosystems: Potential oxidation of northern environments under future change? *Science of the Total Environment* 610, 1496–1504.

Defra (2009). Ecosystem services of peat – Phase 1. Project code: SP0572. Defra, UK.

Defra, (2017). Lowland peatland systems in England and Wales – evaluating greenhouse gas fluxes and carbon balances. Final report on project SP1210.

Gorham, E. (1991), Northern peatlands: role in the carbon cycle and probable responses to climate warming. *Ecological Applications,* 1, 182–195.

Gunther, A., Böther, S., Couwenberg, J., Hüttel, S., and G.Jurasinski (2018). Profitability of including direct measurements of greenhouse gas exchange in monitoring of peatland rewetting for carbon credits. *Ecological Economics* 146, 766–771.

Glenk, K., and J. Martin-Ortega (2018): The economics of peatland restoration, *Journal of Environmental Economics and Policy*. DOI: 10.1080/21606544.2018.1434562

Heinemeyer, A., Croft, S., Garnett, MH., Gloor, E., Holden, J., Lomas, M.R., and P.Ineson (2010). The MILLENNIA peat cohort model: predicting past, present and future soil carbon budgets and fluxes under changing climates in peatlands. *Climate Research* 45, 1, 207-226. Special Issue: 24

Houghton, J.T., Meira-Filho, L.G., Callender, B.A., Harris, N., Kattenberg, A. and K.Maskell (1995). Climate change 1995: The science of climate change. Cambridge, University Press. 339 pp.

IPCC (2013): Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IUCN, 2017. The Peatland Code. IUCN UK Peatland Programme.

JNCC (2011). A review of current evidence on carbon fluxes and greenhouse gas emissions from UK peatlands. JNCC Report No. 442, Joint Nature Conservation Committee, Peterborough, UK.

Le Quere, C. *et al.* (2016). Global Carbon Budget 2016 *Earth Systems Science Data,* 8, 605–649

Loisel, J. et al. (2014). A database and synthesis of northern peatland soil properties and Holocene carbon and nitrogen accumulation. *The Holocene,* 24(9), 1028-1042

Loisel, J., van Bellen, S., Pelletier, L., Talbot, J., Hugelius, G., Karran, D., Yu, Z., Nichols, J. and J.Holmquist (2017). Insights and issues with estimating northern peatland carbon stocks and fluxes since the Last Glacial Maximum *Earth-Science Reviews,* 165, 59–80

Moody, C.S., Worrall, F., Evans, C.D. and T.G.Jones (2013). The rate of loss of dissolved organic carbon (DOC) through a catchment. Journal of Hydrology 492:139–150.

Murphy, J.M., Sexton, D.M.H., Jenkins, G.J., Boorman, P.M., Booth, B.B.B., Brown, C.C., Clark, R.T., Collins, M., Harris, G.R., Kendon, E.J., Betts, R.A., Brown, S.J., Howard, T. P., Humphrey, K. A., McCarthy, M. P., McDonald, R. E., Stephens, A., Wallace, C., Warren, R., Wilby, R., Wood, R. A. (2009), UK Climate Projections Science Report: Climate change projections. Met Office Hadley Centre, Exeter

Nilsson, M., Sagerfors, J., Buffam, I., Laudon, H., Eriksson, T., Grelle, A., Klemedtsson, L., Weslien, P., and A.Lindroth, (2008), Contemporary carbon accumulation in a boreal oligotrophic minerogenic mire – a significant sink after accounting for all C-fluxes. *Global Change Biology*, 14(10), 2317–2332.

Petrescu, A.M.R. (2015). The uncertain climate footprint of wetlands under human pressure. *Proceedings of the National Academy of Sciences of the United States of America,* 112(5), 4594–4599
Roulet, N.T., LaFleur, P.M., Richards, P.J., Moore, T.R., Humphreys, E.R. and J.Bubier, (2007). Contemporary carbon balance and late Holocene carbon accumulation in a northern peatland. *Global Change Biology*, 13, 397–411.
Titterton, P., Benson, J., Thorpe, K., and Pilkington, M. (2022) MoorLIFE2020 Project Carbon Audit Report. Moors for the Future Partnership Report, Edale
Turetsky, M.R., Manning, S.W. and R.K.Wieder (2004), Dating recent peat deposits. *Wetlands*, 24, 324–356.
Worrall, F., Reed, M., Warburton, J., and T.P.Burt (2003), Carbon budget for British upland peat catchment. *Science of the Total Environment*, 312, 133–146.
Worrall, F. and G.D.Clay. (2012). The impact of sheep grazing on the carbon balance of a peatland. *Science of the Total Environment* 438, 426–434.
Worrall, F. and G.D.Clay. (2014). The potential use of heather, Calluna uulgaris, as a bioenergy crop. Biomass and Bioenergy 64, 140–151.
Worrall, F., Evans, M.G., Bonn, A., Reed, M., Chapman, D., and J. Holden. (2009). Can carbon offsetting pay for ecological restoration in uplands? *Science of the Total Environment* 408, 1, 26–36.
Yu, Z.C. (2012). Northern peatland carbon stocks and dynamics: a review. *Biogeosciences,* 9, 4071–4085
Yu, Z., J.Loisel, Cahrman, D.J., Beilman, D.W., and P.Camil (2014). Holocene peatland carbon dynamics in the circum-Arctic region: an introduction. *The Holocene,* 24, 1–7.

Appendix – Example summary results from look up tables

These are just example results that could be generated from the look up table.

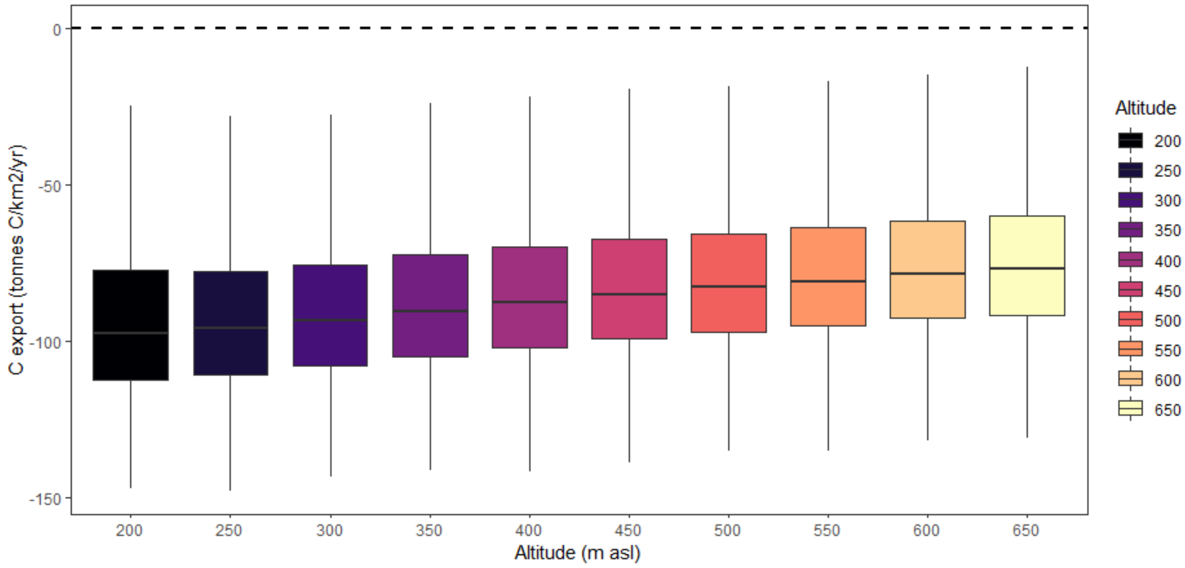

Figure A1. The C export of the Peak District National Park peats summarised by altitude as predicted by the look up table.

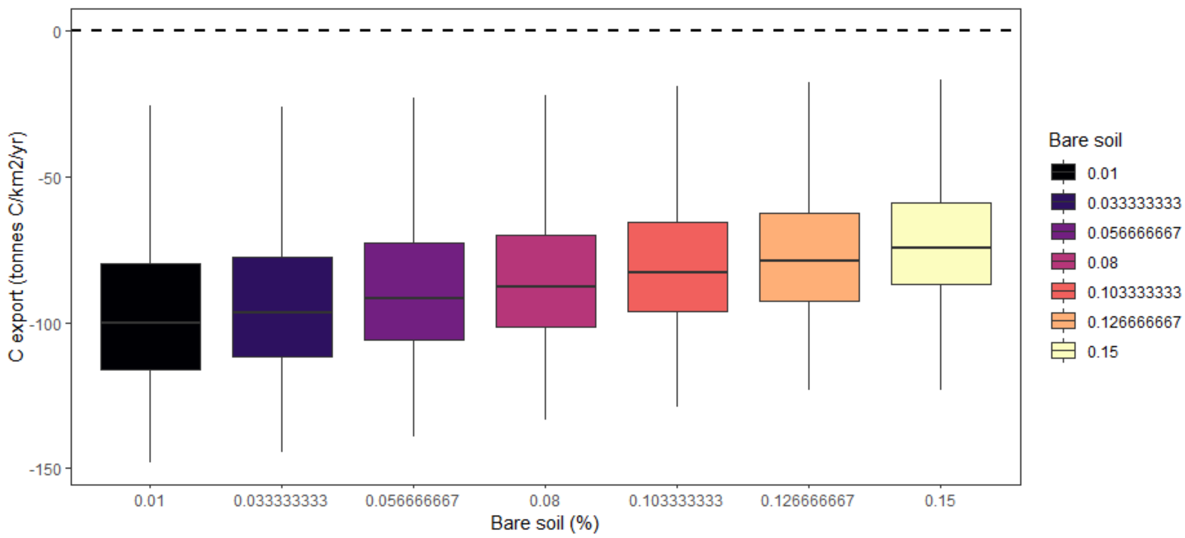

Figure A.2. The C export of the Peak District National Park peats summarised by percentage bare soil as predicted by the look up table.

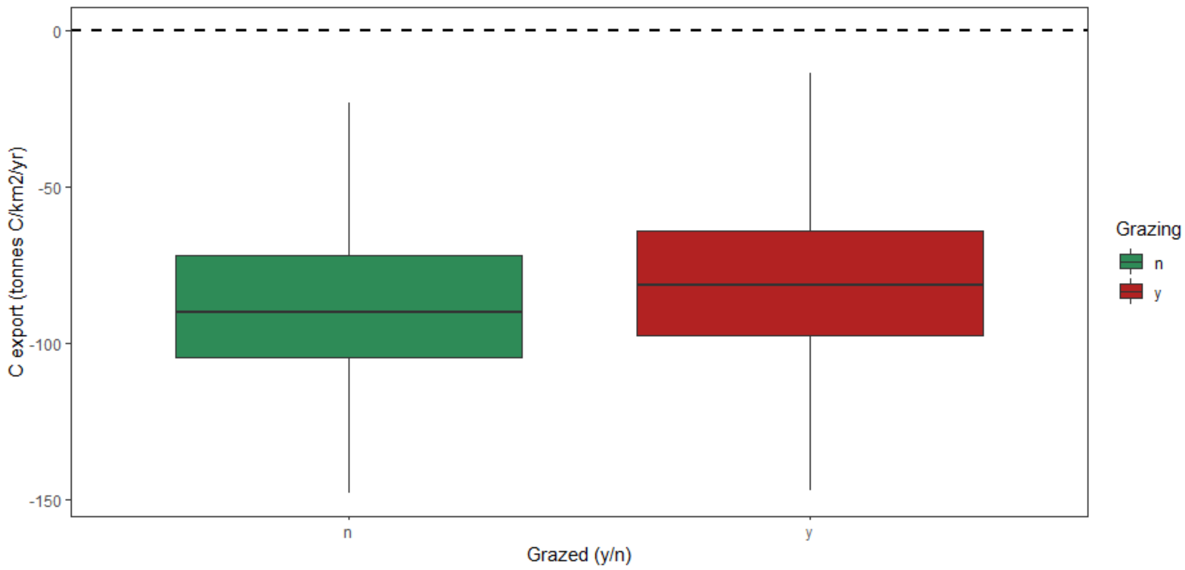

Figure A.3. The C export of the Peak District National Park peats summarised by percentage bare soil as predicted by the look up table.

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

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