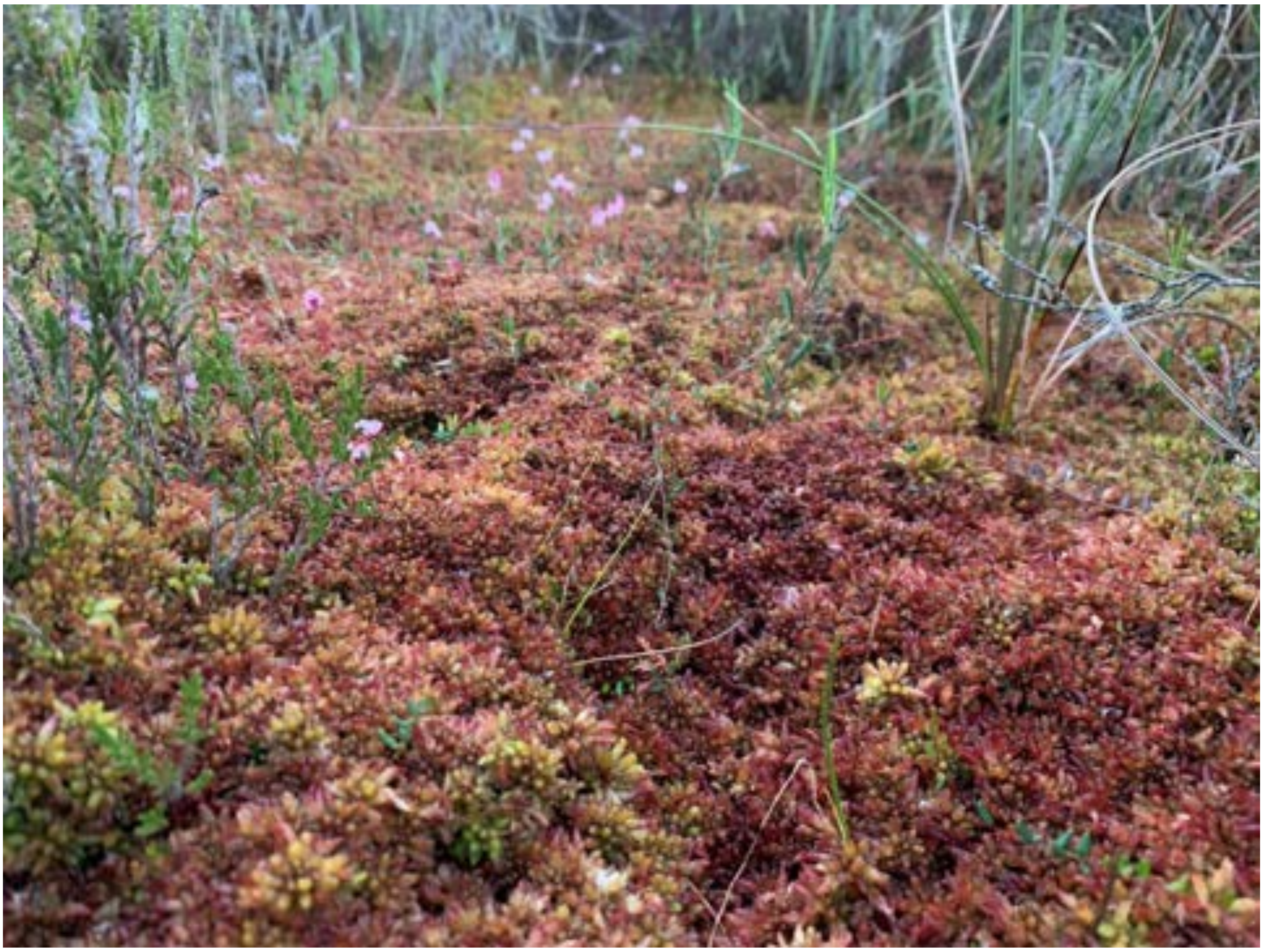
Peatland carbon stock assessment of Fenn's, Whixall and Bettisfield Mosses National Nature Reserve and SAC

Marches Mosses BogLIFE Project (LIFE15/NAT UK/000786) D3



Prepared by: Prof. Fred Worrall, Dept of Earth Sciences, University of Durham, Fred.Worrall@durham.ac.uk, 0191 344 2295.

Restoring Marches Mosses BogLIFE Project (LIFE15 NAT/UK/000786)

Summary

1) The amount of carbon stored in the Fenn's, Whixall and Bettisfield Mosses SAC is estimated to be 1183 ± 99 ktonnes C – this is equivalent to annual greenhouse gas emissions of just over 4 million UK citizens.
2) The Fenn's, Whixall and Bettisfeild Mosses were a net sink of both C and greenhouse gases prior to LIFE project restoration with an estimated sink size of -4.2 ktonnes CO_{2eq}/yr.
3) The LIFE did enhance the magnitude of both C and GHG sinks across the Fenns and Whixall Mosses with an estimated sink size of -4.3 ktonnes CO_{2eq}/yr.
4) Further improvements in the magnitude of the greenhouse sink on Fenns and Whixall by further development of sphagnum mosses - estimated sink size of -5.2 ktonnes CO_{2eq}/yr – this is the annual emissions of almost 1000 UK citizens.
5) The capacity for further storage is vast, estimated at 7 Mtonnes CO_{2eq}, although to realise this potential techniques for enhanced carbon storage on the Mosses would be required
6) The carbon storage on the Mosses could now be monitored remotely through Earth observation.

1) Background

The very existence of peatland is because, at some stage, in the life history of the peatland the organic matter has been able to accumulate and so the carbon budget of that peatland is an expression of the health of a peatland and its sustainability. That past and present accumulation of organic matter means that peatlands are not only a store of carbon but can be an ongoing sink of atmospheric carbon. The fundamental importance of the carbon budget to the very existence of peatlands means that any ambition for a peat ecosystem must start with assuring the sustainability of the organic matter accumulation. Therefore, to assess the restoration of Marches Mosses BogLIFE project it is critical to assess the carbon stock and sink represented by the mosses.

The Marches Mosses BogLIFE project is a six year project running from 1 October 2016 to 31 December 2022. The project aims to restore Britain's 3rd largest lowland raised bog within the Fenn's, Whixall & Bettisfield Mosses and Wem Moss NNRs near Whitchurch, Shropshire and Wrexham in Wales. The LIFE project is led by Natural England working in partnership with Natural Resources Wales and the Shropshire Wildlife Trust. The project is financially supported by LIFE, a financial instrument of the European Commission and the National Heritage Lottery Fund.

The 'project area' is 781 ha ie the area declared as NNR in August 2022. The NNR covers 82% of the Fenn's, Whixall, Bettisfeild, Cadney and Wem Mosses SAC/SSSI which has an area of 948 ha (Figure 1).

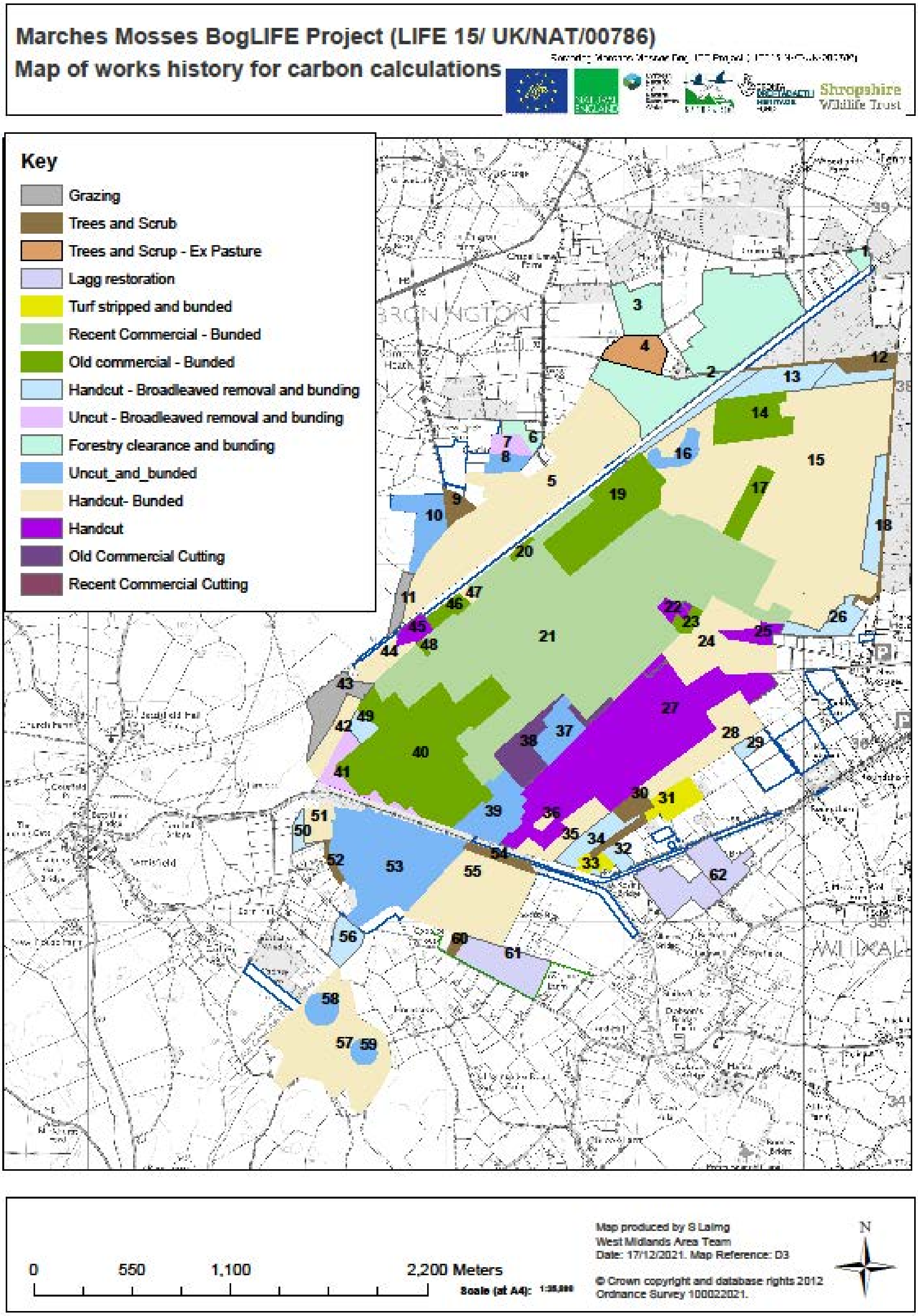


Figure 1. The Fenn's, Whixall & Bettisfield Mosses and Wem Moss NNR with management units labelled. By necessity of data coverage the area covered within this study is sometimes the NNR and sometimes the SAC area and where this is the case the difference has been noted.

2) Aim and objectives

The aim of this work was to quantify the carbon and greenhouse gas benefits of the restoration works conducted under the project, more specifically it will:

i) Following a desk-based approach, using data from site monitoring etc and published sources, evaluate the impact restoration works have had on peat stabilisation, peat formation and greenhouse gas emissions across the area of the EU LIFE project at Fenn's, Bettisfield and Whixall Mosses.
ii) Estimate carbon stocks held within Fenn's, Bettisfield, Whixall and Wem Mosses SAC (larger than the Project area) . This estimate should include both carbon stored in the peat and above ground carbon.

3) Approach & Methodology

Our approach to meeting these objectives will be to estimate the carbon and greenhouse gas budgets for the area of the LIFE project using the Durham Carbon Model and to assess the carbon stock based upon peat depth observations supplied by Natural England for the Marches Mosses and also from our own work on Whixall Moss.

3.1) Estimation of the carbon stock

To estimate the current carbon stocks it is necessary to know several things:
Peat depth – here we would propose to map the peat depth across the Mosses.
Peat profile properties – explicitly for the carbon stock we need values for the density and carbon content profile of the peat. We have previously sampled and analysed for bulk density and carbon content of two peat cores for Whixall Moss (Clay and Worrall, 2015). Furthermore, we have analysed peat cores from lowland peat across the UK (8 sites reported in Clay and Worrall, 2015), and 5 more unpublished cores as part of Defra lowland peat project - Defra, 2016). The collection of peat profile properties means that we can both provide local values and assess the uncertainty on those values.
Biomass content and composition – to estimate the carbon stock in the biomass it is necessary to know:

- Area of each vegetation type – this will be taken from the description of the management unit provided by Natural England staff.
- Biomass per unit area or coverage – for typical peatland vegetation this can be taken from a number of published sources (eg. Forrest, 1971) or from biomass models such as we have used in Worrall and Clay (2012) based on Armstrong et al. (1997).
- Carbon content – as with peat profiles we are fortunate that within studies such as that Clay and Worrall (2015) the carbon content of vegetation has been analysed for typical peat vegetation, but also a range of such vegetation from other peatland sites

3.2) Evaluation of the impact of restoration works on carbon and greenhouse budgets

The calculations will be based upon the application of the Durham Carbon Model (DCM - Worrall et al., 2009). The DCM was developed as a model for the contemporary fluxes of Carbon and GHG from managed peatlands. The model at the core of that approach has been developed in a number of ways since the original publication and with especial reference to this project the modelling now includes:
Land management types – the DCM includes arrange of management types and can model changes in drainage, grazing, forestry, bare soil, open water and scrub removal.
Vegetation types – the model can now estimate for: *Calluna vulgaris*, sedges, bracken, trees, shrubs, grasses, mosses (including *Sphagna*) and any combination of these within a management unit.
Gullying and drainage – given the dugover nature of the Marches Mosses the DCM model can model the cutover features as gullies. The DCM can handle gully spacing between 3 and 25 m, for spacings closer than 3 m our model is not defined and for greater distances than 25 m there is no further impact and drainage then becomes no different from that expected of natural drainage. At spacings greater than 25 m then it is feasible to consider the cutover features as separate management units as distinct. For sites where there is artificially created topography, such as dugover peatlands, then there the transition sink represented by the

infilling of such features. The carbon sink represented by transition sinks will be estimated given the approach to carbon stock estimation outlined below.

The DCM is a pseudo-2D model which the spatial scale at which models can be set to the scale of management units within the Mosses. The management units modelled for this study are shown in Figure 1. For each model unit the following are required:

- *Area* – the area of each model unit can be calculated from supplied maps. Typically, a model unit is a management unit where a particular set of inputs is true.
- *Altitude* – derived from local DEM.
- *Area of peat* – it might be that any model unit is not 100% peat.
- *Vegetation cover* – the DCM can cope with several different types of vegetation at a functional group level. The vegetation types included are: forest, grasses, heather, sedges, non-sphagnum mosses; and sphagnum mosses These classes are not further sub-divided, for example, sedges are not divided down to cotton grass species The assessment of vegetation cover also includes the presence of bare peat. For previous modelling of LIFE sites the available vegetation surveys were classified in to these functional groups and bare soil area. Note that within restoration scenarios we do include the transitionary sink of changing stock of biomass, but these are considered separately as transitonary sinks.
- *Open water* – we do not expect there to be large areas of open water in this particular study.
- *Management* – it is possible within the model to set characteristics of each model/management unit that are then changed with restoration. It will be possible to include a range of interventions within the modelling, a priori these could include: bare peat restoration, plug planting (e.g. cotton grass), cutting, Rhododendron removal, and reprofiling.

To measure the impact of the peat restoration works have had on the carbon and greenhouse gas budgets we would suggest a series of model scenarios:

a) Post-restoration – this is the present day scenario - the models can be used for estimating the current carbon and greenhouse gas budgets. This scenario is aimed at measuring the present carbon and GHG budget of the restored areas; and
b) Pre-restoration – this is the counter-factual scenario – for estimating the benefit of intervention on the sites it is important to estimate what would have been the current case if no intervention had occurred. Thus scenario includes an estimate of the carbon and greenhouse gases fluxes had no intervention taken place, i.e. an estimate of the flux after the cessation of peat extraction on the site and without any restoration.
c) Optimised – in this scenario the management for each unit will changed so as maiximise the greenhouse gas sink of that management unit.

3.3) Model limitations

It should always be noted that this is a modelling exercise and not based upon actual field measurements and as such the results are always constrined by the limits of the model and its assumptions. Of particular note with respect to modelling the Marches Mosses there are two limitations to note. Firstly, that the DCM does not include an ecological trajectory whether that is with or without restoration. Although the DCM considers a 10 year period this length of time is used to average out climate effects rather than natural ecological change. The vegetation cover within any model scenario was fixed relative to information provided by Natural England staff: that vegetation cover does not change through the modelling time steps. It would be expected that vegetation cover would evolve over time after restoration activity and thus there might be ongoing improvements in carbon and greenhouse sequestration.

The second major limitation of the DCM with respect to use on the Marches Mosses is that the DCM has never previously been applied to lagg communities. Within this project the management units identified as lag communities have been modelled within the constrains of a model never designed for lag ecosystems.

3.4) Project Deliverables

The project will deliver:

- An estimate of the current greenhouse gas emissions of the Marches Mosses BogLIFE project area.
- An estimate of the amount of greenhouse gas emissions saved by the restoration works
- An estimate of the current carbon stock of Marches Mosses.

4) Results

4.1) Carbon stock

The peat profile properties are shown Figure 2 and these are integrated to give the total C to given depth in Figure 3 and Equation (i).

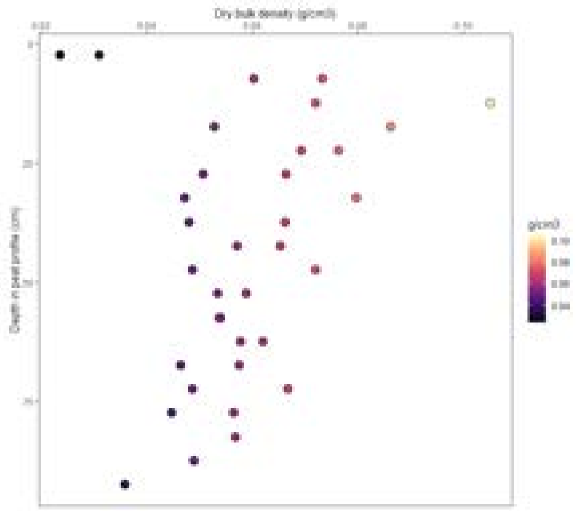


Figure 2. The profile of dry bulk density for Whixall Moss. Note that two cores were taken and values for both cores are plotted.

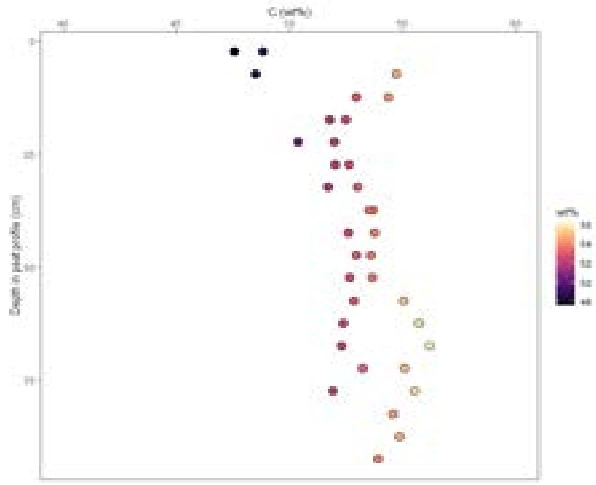


Figure 3. The profile of the weight percent carbon content for Whixall Moss. Note that two cores were taken and values for both cores are plotted.

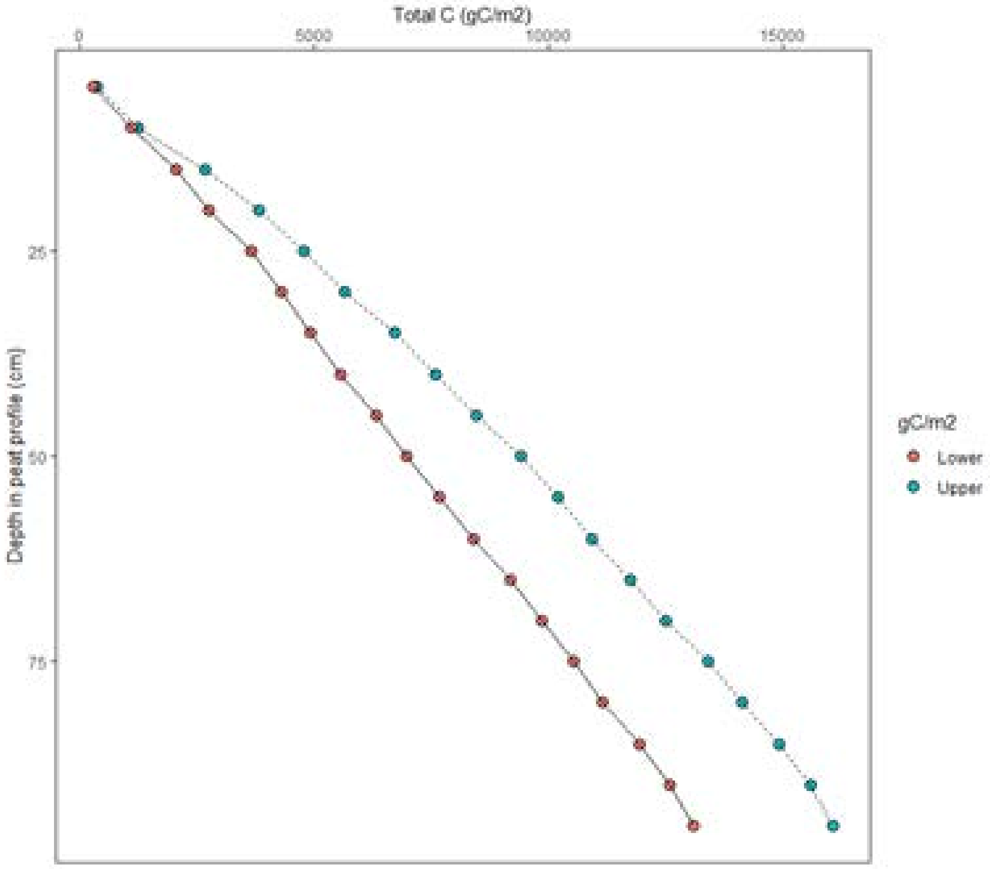


Figure 4. The profile of the integrated total C to depth for Whixall Moss. The two curves represent the lower and upper limits of the 95th percentile confidence interval.

The best-fit equation for total C to depth is:

$TotalC = 158depth$ n=529, $r^2 = 0.94$ (i)

(6)

Where: TotalC= integrated total C to a given depth (gC/m^2); and depth = depth of peat (cm). The value in the bracket below Equation (i) is the standard error in the coefficient. Note that in Equation (i) there was no significant intercept value and this is entirely reasonable as there is no C storage at zero depth.

The depth measurements were supplied by Natural England (Appendix 1) and show a considerable depth of peat remains on the site within the SAC area (Figure 5).

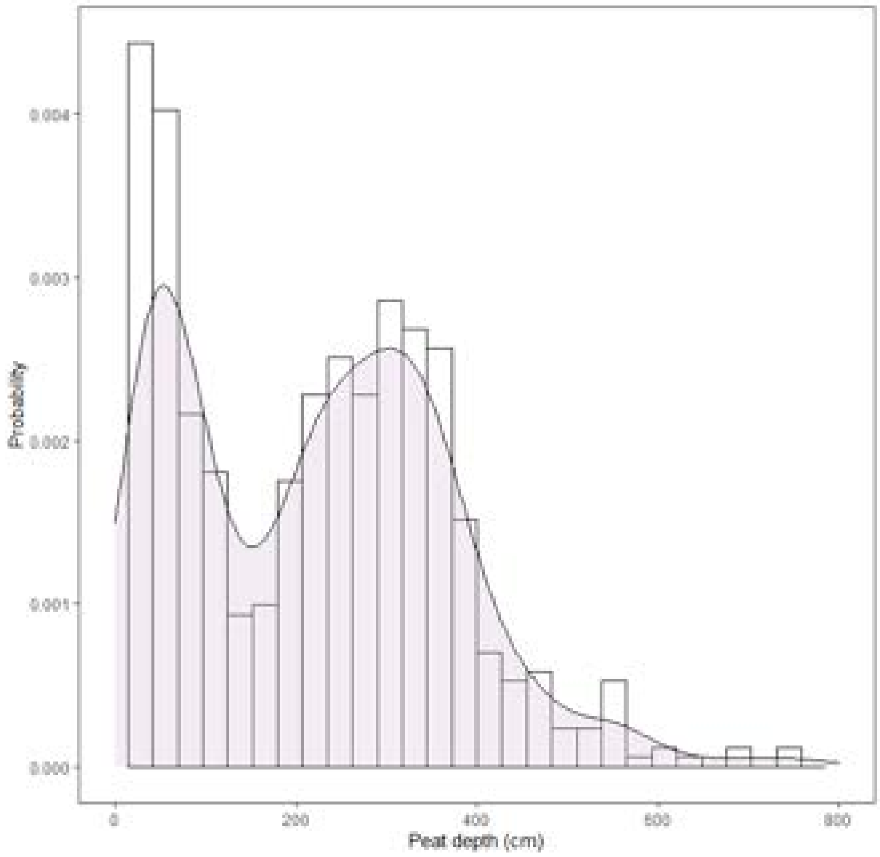


Figure 5. The distribution of peat depths measured for Fenns and Whixall Mosses SAC area. The modelled probability density function is given.

The total carbon stored in the Fenn's and Whixall Mosses SAC area is given in Table 1. The aboveground carbon stock (biomass) was 0.6 ktonnes/km2, or approximately 6 ktonnes C, i.e. > 1% of the total C storage on the Mosses.

Table 1. The total carbon storage and carbon density for the Fenns and Whixall Mosses within the SAC area.

	Total Carbon storage (ktonnes C)	C density (tonnes C/ha)
Mean	1183	1191
Lower confidence limit	1084	1120
Upper confidence limit	1282	1324

For comparison the carbon density at Thorne Moors was up to 420 tonnes C/ha but as low as 160 tonnes C/ha and estimated total carbon stock of 359 – 439 kt C, giving an average C density of 191 tonnes C/ha. For Hatfield Moors the estimated C storage was between 280 – 312 ktonnes C with a C density of 156 tonnes C/ha. For the Cumbrian lowland bog sites: Bolton Fell Moss the belowground biomass was 312 ktonnes C; 1332 ktonnes C for Wedholme and 456 ktonnes C for Roudsea Moss, that gives respective C areal density of: 1190 tonnes C/ha; 2960 tonnes C/ha; and 944 tonnes C/ha. The difference between values at Fenn's and Whixall and the C storage of the Thorne and Hatfield Moors is the difference in peat depth – the average peat depth at Fenns and Whixall is 230 cm while for Thorne Moors it is 85 cm.

The carbon content and dry bulk density measured at other peat sites across the UK are shown in Figures 5 and 6; and shows that the Marches Mosses are not exceptional.

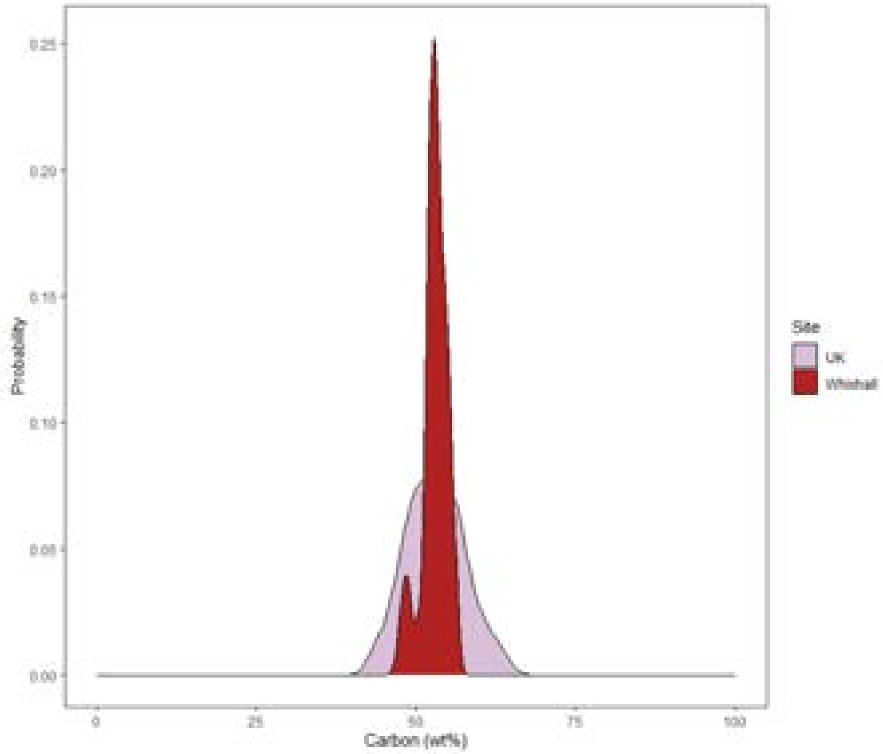


Figure 6. The probability density of the carbon content measured at Fenns and Whixall Mosses in comparison to results measured for 12 other UK peatlands.

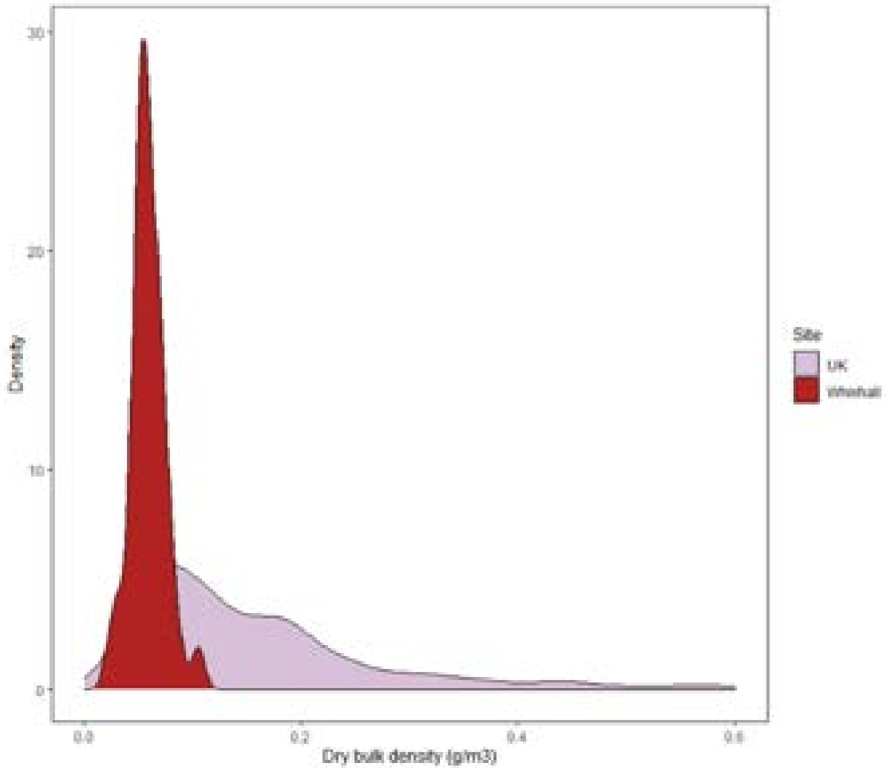
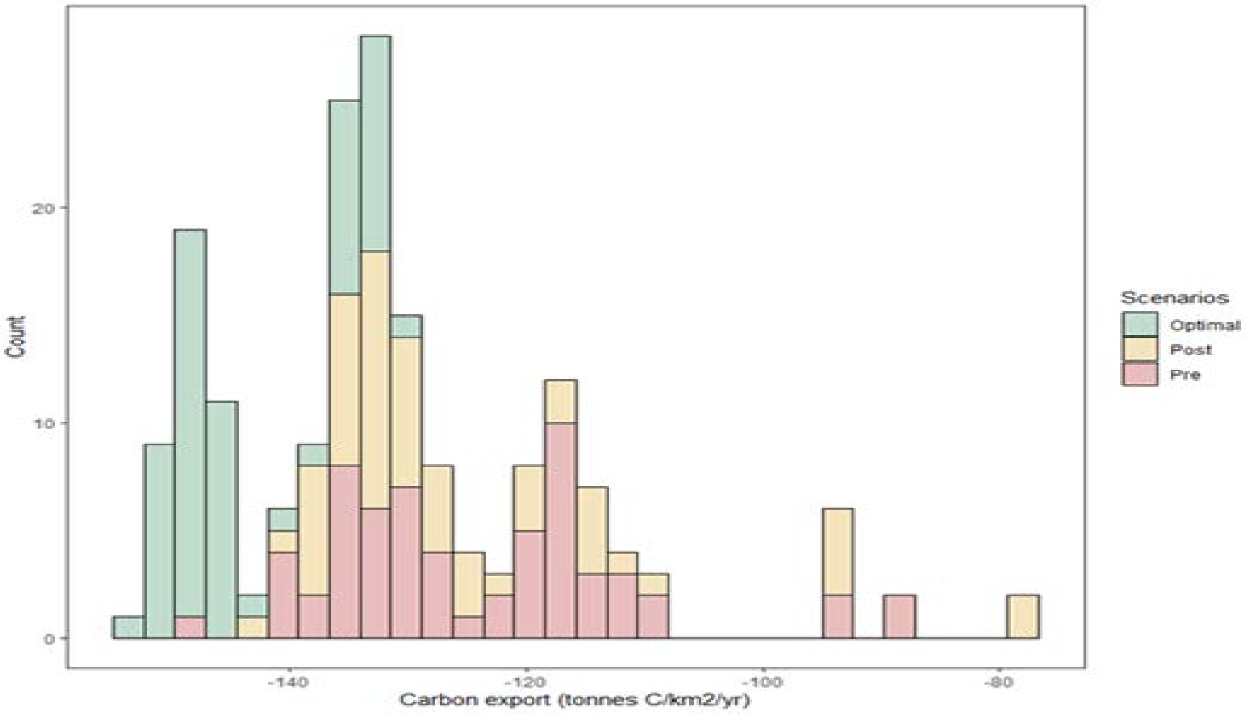


Figure 7. The probability density of the dry bulk density measured at Fenn's and Whixall Mosses in comparison to results measured for 12 other UK peatlands.

4.2) Carbon and GHG flux

The model results estimate that for the pre-LIFE project scenario average export of C is -122 tonnes C/km^2/yr; for the post-LIFE s project scenario it is -125 tonnes C/km^2/yr; and for optimised scenario it is -143 tonnes C/km^2/yr. When scaled to the size of the Fenn's and Whixall Mosses SAC area this would give an total estimated sink size of -1161 tonnes C/yr. Figure 7 shows that all management units could be considered sinks prior to the LIFE project and Figure 8 shows that the LIFE project did increase the C sink, albeit by a small amount, for the majority of the management units. Example output for the pre-LIFE scenario is given in Table 2 and for other sceanrios in the Appendix.



F*igure 8. The distribution of C export from the management units on the Marches Mosses as calculated for the pre- and post-restoration scenarios; and optimal scenarios. NB. C export values are expressed as relative to atmosphere and so a negative value represents a sink of carbon from the atmosphere, and shifts to left along the x-axis of this Figure are improvements in sink size.*

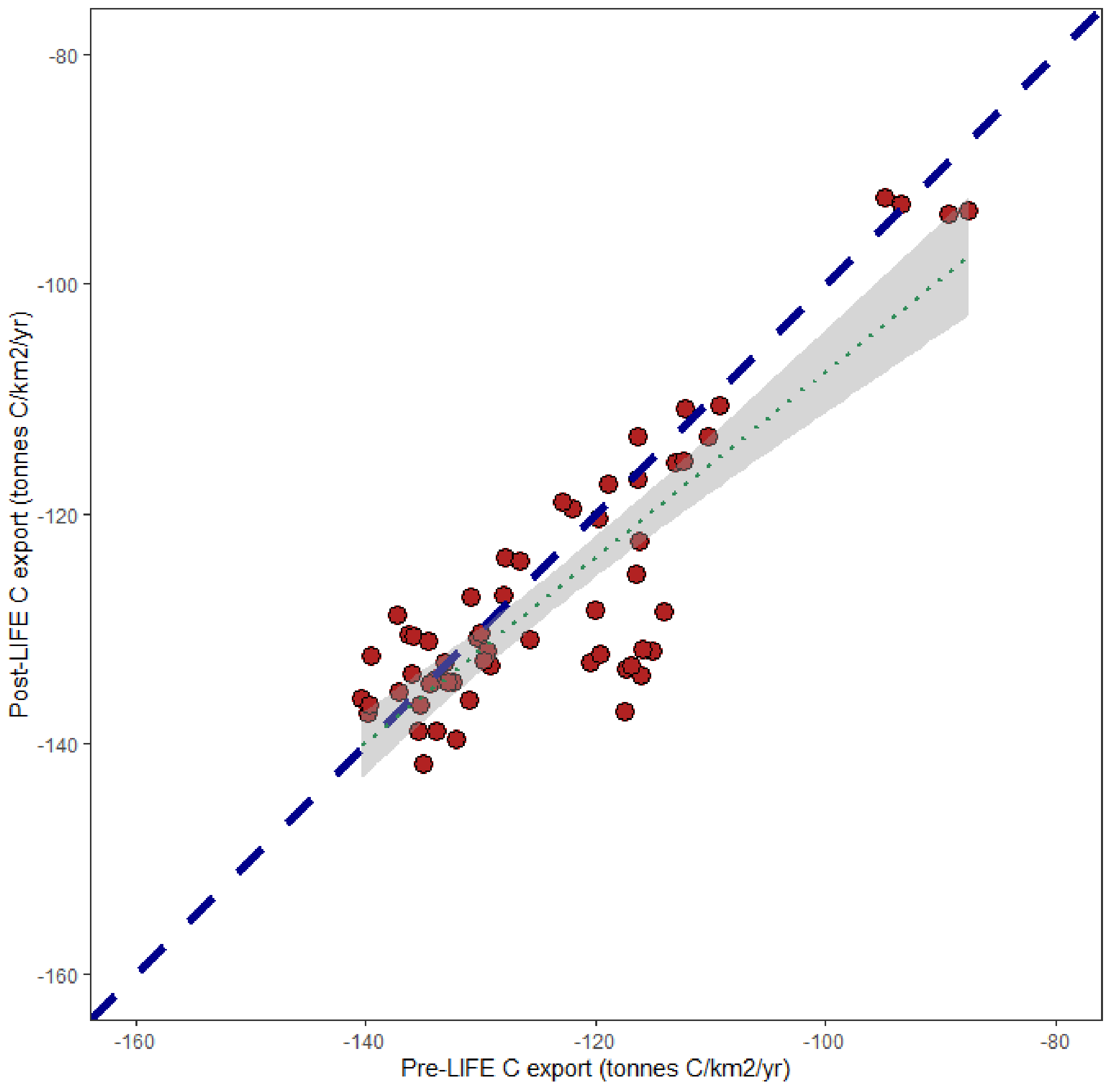


Figure 9. Comparison of the pre- and post-LIFE restoration C export for each management unit. The 1:1 line (---)

A similar pattern of results to that for C export was found for GHG export, i.e. there are no management units that are predicted to be net sources of either C or GHG (Figure 10 and 11).

Table 2. The C and CO_2 export from the management units of Fenn's and Whixall Mosses based upon a pre-LIFE restoration state. The management units are given in Figure 1.

Management unit	Description	Export (tonnes X/km^2/yr)	
		C	CO_2
1	Forestry Clearance and bunding	-114.3	-442.6
2	Forestry Clearance and bunding	-115.5	-452.3
3	Forestry Clearance and bunding	-112.3	-443.3
4	Trees and Scrub - Ex pasture	-119.8	-453.0
5	Handcut- Bunded	-132.7	-490.8
6	Forestry Clearance and bunding	-118.2	-449.5
7	Uncut- Broad leaved removal and bunding	-117.9	-449.7
8	Uncut - bunded	-137.7	-501.3
9	Trees and scrub	-119.2	-460.0

10	Uncut and bunded	-134.7	-500.1
11	Grazed	-123.3	-468.0
12	Trees and Scrub	-121.7	-452.6
13	Handcut- Broadleaved removal and bunding	-116.2	-456.0
14	Old commercial - bunded	-137.0	-500.6
15	Handcut - bunded	-128.5	-484.1
16	Uncut and bunded	-137.7	-512.2
17	Old commercial - bunded	-136.4	-497.1
18	Handcut -Broadleaved removal and bunding	-119.5	-452.5
19	Old commercial - bunded	-136.8	-503.7
20	Old commercial - bunded	-133.2	-493.0
21	Recent Commercal - Bunded	-133.0	-495.9
22	Hand cut	-133.0	-493.3
23	Old commercial - bunded	-134.9	-497.8
24	Handcut - bunded	-134.3	-498.5
25	Handcut	-137.0	-498.8
26	Handcut - Broadleaved removal and bunding	-121.1	-449.6
27	Handcut	-128.6	-476.5
28	Handcut - bunded	-132.2	-494.0
29	Handcut - Broadleaved removal and bunding	-115.9	-446.5
30	Tree and Scrub	-121.2	-454.2
31	Turf Stripped and bunded	-134.9	-495.0
32	Handcut - Broadleaved removal and bunding	-124.7	-462.9
33	Turf Stripped and bunded	-139.9	-505.5
34	Handcut - Broadleaved removal and bunding	-116.7	-447.6
35	Handcut -bunding	-133.3	-494.6
36	Handcut -bunding	-139.3	-500.7
37	Uncut and bunded	-134.0	-495.9
38	Old commercial cutting	-133.3	-497.2
39	Uncut and bunded	-139.9	-507.5
40	Old commercial - bunded	-131.2	-485.4
41	Uncut - Broadleaved removal and bunding	-114.9	-448.5
42	Handcut - bunded	-92.8	-343.1
43	Grazed	-139.2	-508.1
44	Handcut bunded	-91.3	-339.3
45	Handcut	-94.2	-343.8
46	Old commercial - bunded	-90.5	-335.0
47	Handcut - bunded	-94.0	-347.1
48	Old commercial - bunded	-90.8	-342.5
49	Handcut- Broadleaved removal and bunding	-115.7	-438.5
50	Handcut - Broadleaved removal and bunding	-118.7	-456.9
51	Handcut - bunded	-92.2	-343.5
52	Tree and Scrub	-122.8	-457.2
53	Uncut and bunded	-91.5	-341.7
54	Tree and Scrub	-113.4	-445.5
55	Handcut - bunded	-94.1	-345.9
56	Handcut- Broadleaved removal and bunding	-116.9	-447.4
57	Handcut - bunded	-90.6	-340.4
58	Uncut and bunded	-92.6	-341.4
59	Uncut and bunded	-92.4	-342.4

60	Trees and Scrub	-110.3	-443.2
61	Lagg restoration	-136.7	-509.1
62	Lagg restoration	-137.5	-502.5

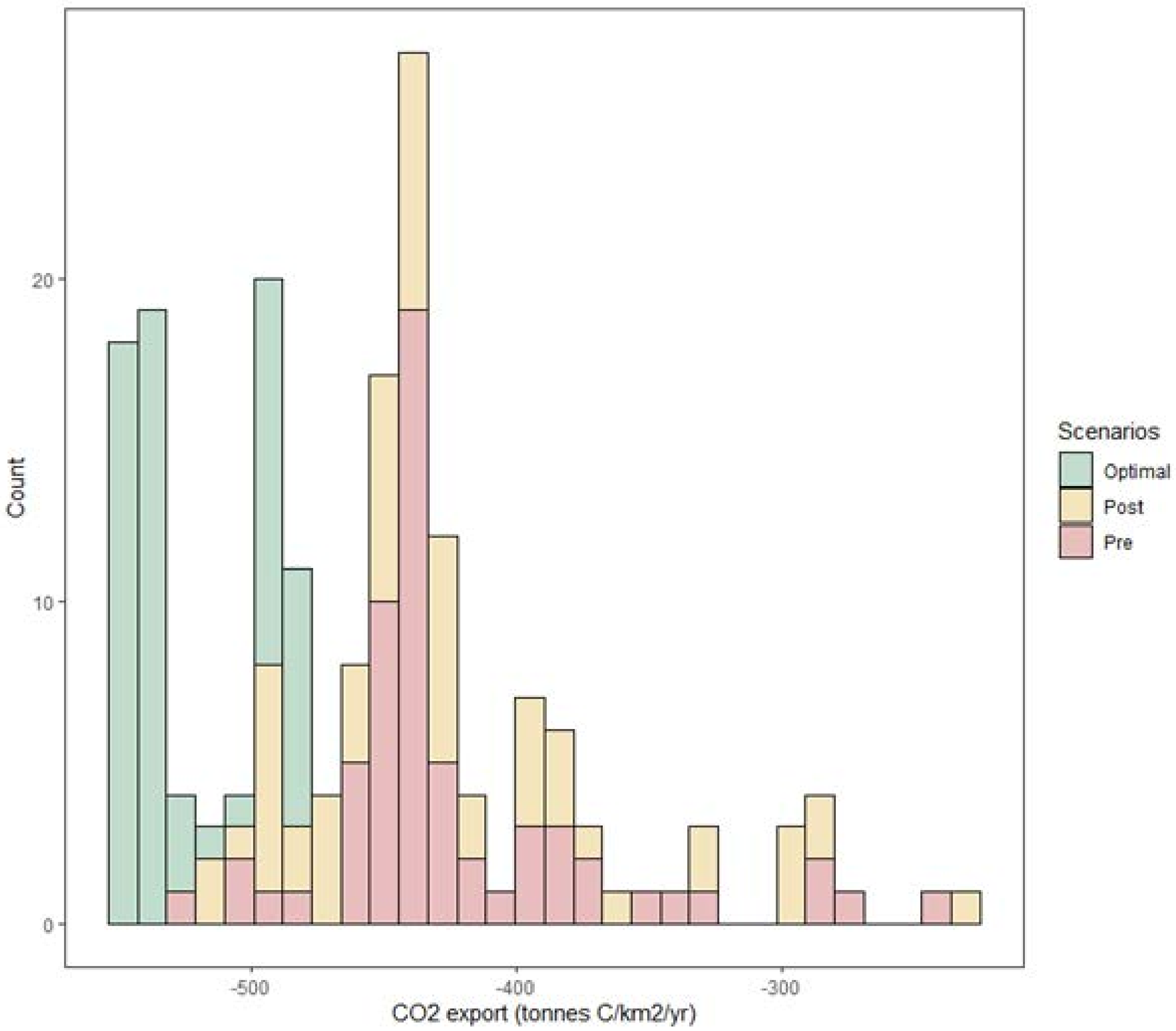


Figure 10. The distribution of GHG export from the management units on the Marches Mosses as calculated for the pre- and post-restoration scenarios; and optimal scenarios. NB. GHG export values are expressed as relative to atmosphere and so a negative value represents a sink of carbon from the atmosphere, and shifts to left along the x-axis of this Figure are improvements in sink size.

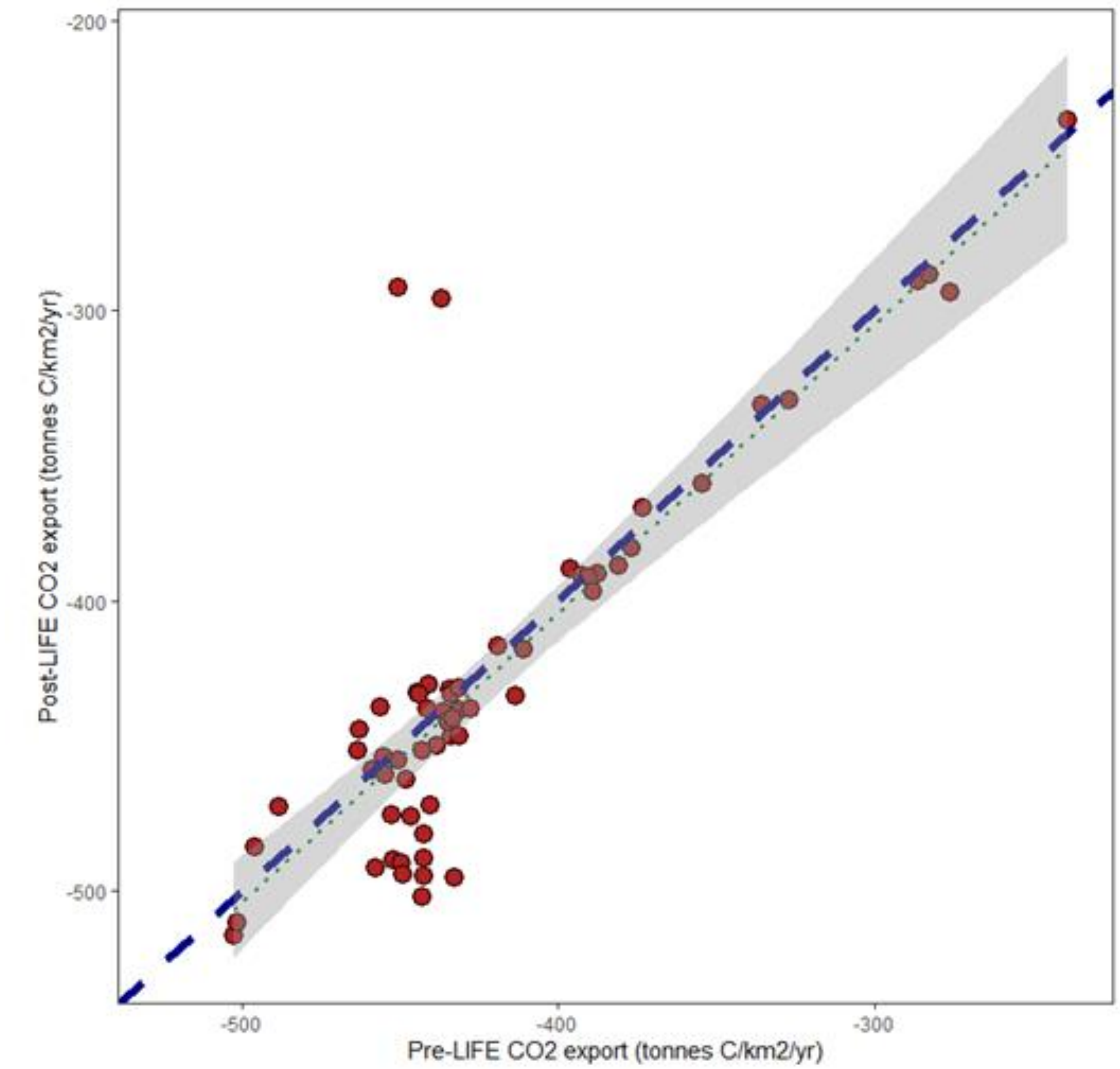


Figure 11. *Comparison of the pre- and post-restoration GHG export for each management unit. The 1:1 line (---).*

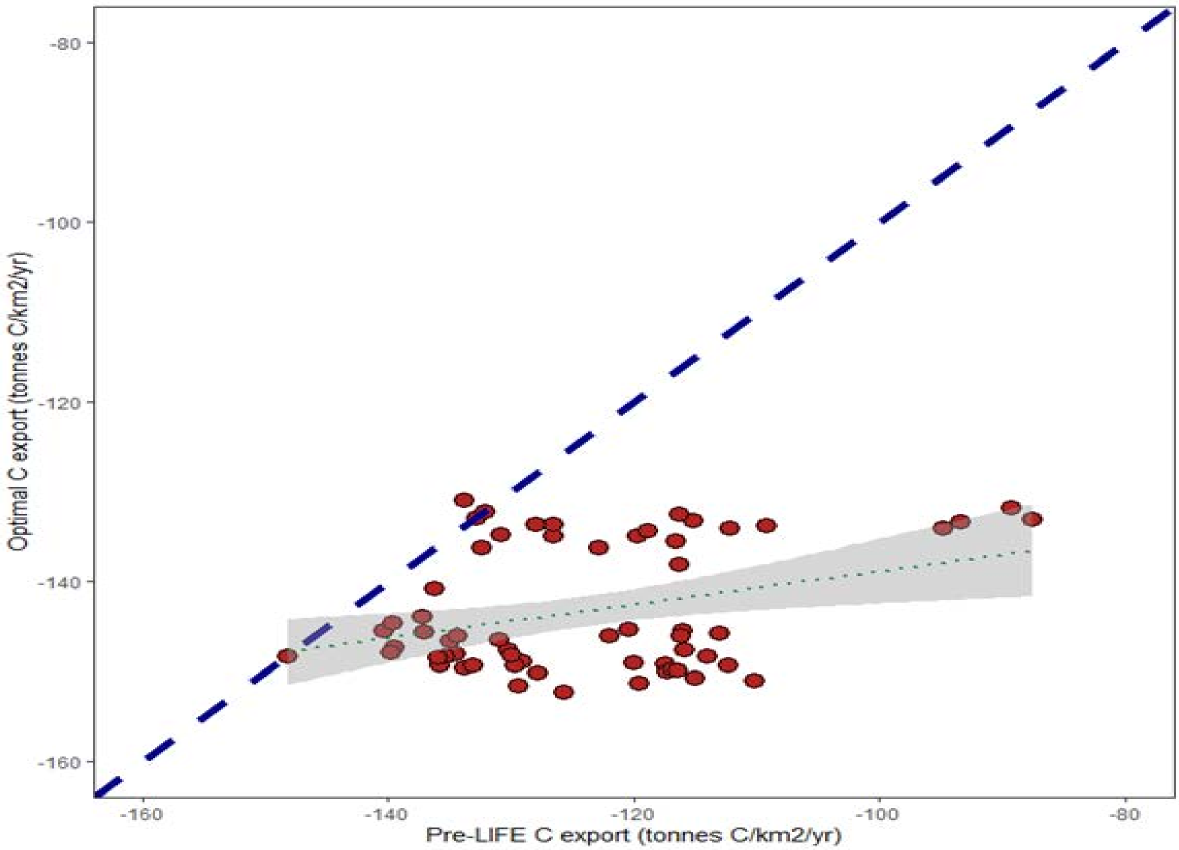


Figure 12. Comparison of the pre-restoration and optimised GHG export for each management unit. The 1:1 line (---).

Table 3. Summary of median export results for the different scenarios.

Scenario	C export (tonnes C/km^2/yr)	GHG export (tonnes CO_{2eq}/km^2/yr)
Post-extraction	+72	+260
Pre-LIFE	-123	-423
Post-LIFE	-125	-425
Optimal	-143	-523

As noted above, the DCM cannot predict an ecological trajectory and it woul, therefore, be expected that the benefit of the LIFE project would improve over time. It is not surprising that the results for the Optimisation scenario show increases in GHG export relative to pre-LIFE scenario (Figures 10 & 11). The optimal C export was -153 tonnes C/km^2/yr, or a sink for Fenn's and Whixall Mosses of 1481 tonnes C/yr. The current estimate of the average export of greenhouse gases is -550 tonnes CO_{2eq}/km^2/yr, or a sink for Fenn's and Whixall of 5321 tonnes CO_{2eq}/yr. The range of results from the optimal scenario were compared by percentage sphagnum or sedge cover within the management unit (Figure 13) and, perhaps unsurprisingly, show that the largest sink was achieved with the highest percent cover of sphagnum mosses. Creevy et al. (2020) measured the net ecosystem exchange for three forest-to-bog restoration sites across Fenn's and Whixall Moss. The net ecosystem exchange as measured by Creevy et al. would correspond to the C export, but not the GHG export, and they found a C export of −131 tonnes C/km^2/yr for the oldest restored area (17 years post restoration) which is well within the range estimated by the modelling exercise.

A different perspective on the results and the work on the Marches Mosses can be obtained by comparing the values for the pre- and post-LIFE restoration scenarios to that the C and GHG export immediately after cessation of peat extraction, and therefore before any restoration activities had taken place. The median C export prior after the cessation of extraction was +71.8 tonnes C/km^2/yr and a median GHG export of +260.2 tonnes CO_{2eq}/km^2/yr, note that in both the cases of C and GHG export was a source to the atmosphere. Creevy et al. (2020) found that the net ecosystem exchange of the youngest restoration area (6 years post-restoration) that they studied was a net source of 35 tonnes C/km^2 yr. Comparing the export after cessation of peat extraction with that after restoration of the LIFE project the saving of the LIFE project relative to the immediate post-extraction was then a median saving of 195 tonnes C/km^2/yr or 685 tonnes CO_{2eq}/km^2/yr and if the optimal management was considered then the saving, relative to export immediately after the cessation of peat extraction, was as large as 783 tonnes CO_{2eq}/km^2/yr.

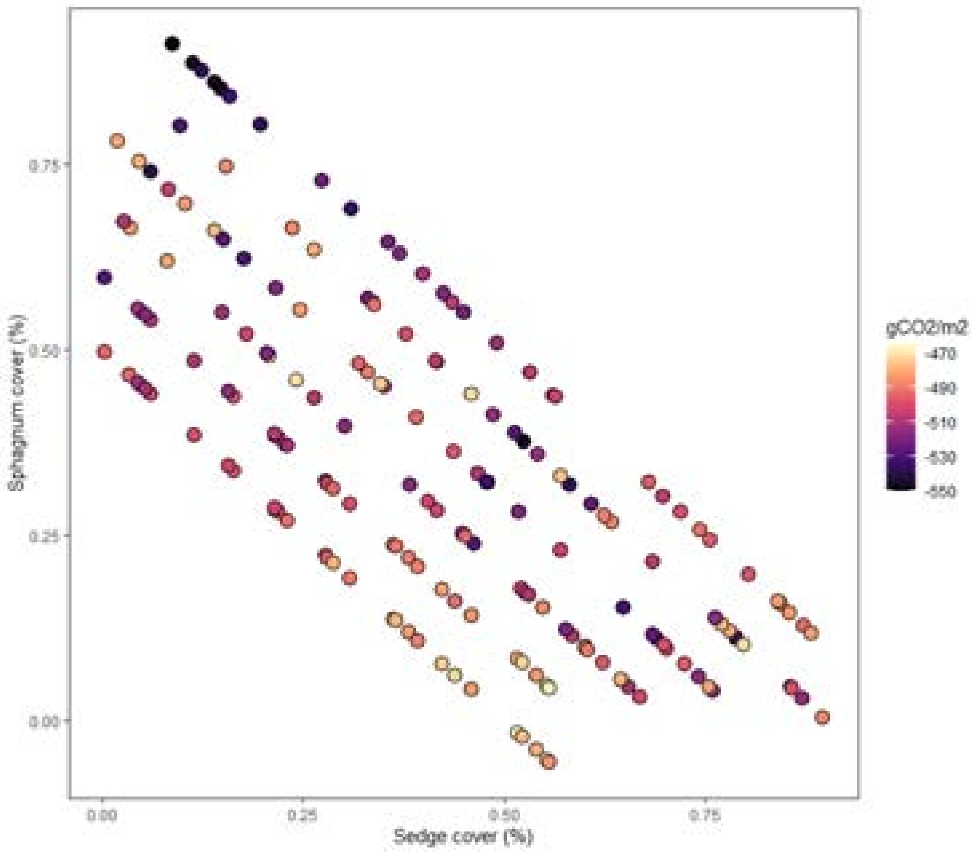


Figure 13. The greenhouse gas flux predicted for optimal strategies using combinations of heather, sedge and sphagnum cover.

4.3) Comparison with other UK lowland raised bogs

For comparison we can examine values for other lowland raised bogs in England. For Bolton Fell Moss (Table 4) the C and GHG export for intact areas (never dugover for peat) is in the range predicted for the Fenn's and Whixall Mosses. Export estimates for Thorne and Hatfield Mosses are lower than those for the Fenn's and Whixall Mosses but at Thorne and Hatfield Moors there were no intact areas.

Table 4. Summary of the pre- and post-restoration carbon and GHG budgets for Bolton Fell Moss. The budgets are expressed as exports (flux per unit area) and results are average for the Intact areas (never dug for peat and not restored) and Dugover areas (those areas extracted for peat and the focus of LIFE project restoration).

	Carbon (tonnes C/km^2/yr)		Greenhouse Gases (tonnes CO_{2eq}/km^2/yr)	
Compartment	Pre-restoration	Post-restoration	Pre-restoration	Post-restoration
Intact	--121	-123	-430	-433
Dugover	15	-3.5	34	-6

Table 5. Summary of the carbon and GHG budgets for Thorne and Hatfield Moors. The budgets are expressed as exports (flux per unit area) and results are average for the dugover areas (those areas extracted for peat and the focus of LIFE project restoration) – there are no intact areas on the Thorne and Hatfield Moors.

Compartment	Carbon (tonnes $C/km^2/yr$)		Greenhouse Gases (tonnes $CO_{2eq}/km^2/yr$)	
	Pre-restoration	Post-restoration	Pre-restoration	Post-restoration
Dugover	--41	-50	-158	-176

2) Future Work

5.1) Enhanced greenhouse gas storage

The results from this study illustrate a growing finding from peat land carbon studies, that although peatlands can store very considerable quantities of carbon, the sink sizes that can be achieved are less than would currently be economic or competitive with other nature-based greenhouse gas removal techniques, in particular in comparison to tree planting which has a large magnitude impact on the timescale of net zero targets. However, the capacity of lowland raised bogs is massive – we only have to consider the difference between the average and deepest peat depth recorded across the Mosses to see the potential. The difference between the average and deepest peat was approximately 4 m, at the density and C content measured at Whixall then the missing peat from Whixall Mosses is approximately 1.9 Mtonnes C or 7 Mtonnes CO_{2eq}. The potential capacity of Whixall Mosses represents offsetting the total GHG output of 1.29 million people, or 46,000 people taken to net zero for between now and the UK government target of 2050. However, at current C budgets the capacity would only be realised over a period of millennia and not over the period being set by UK government for net zero, and so, how could the greenhouse gas sink size of Marches Mosses be enhanced?

There are several possible techniques for enhancing carbon storage on peatlands that would work above and beyond the current standard restoration techniques (eg. development of extensive sphagnum growth). The possibilities rely on bringing in natural sources of organic matter on to the site to build up the peat surface at the maximum rate which does not swamp the peat-forming vegetation. The two current possibilities are use of either wood chip or biochar. Both these amendments could be experimented with and areas of open water are, nothwithstanding other impacts or non-carbon storage issues, particular good targets for infilling (Figure 14.

F*igure 14. Example of pond in a dugover cell at Whixall which represents ready capacity to be infilled with naturally available organic matte rand so enhance the carbon sink within the Marches Mosses.*

5.2) Radiocarbon dating

To measure the available capacity at Whixall we need to measure the historic carbon accumulation rate, and so know the where the peat surface would have been had no peat extraction taken place. The difference between the current peat surface and that projected peat surface represents the available natural capacity of the Mosses. Because we already had a peat core from Whixall Moss we have sent eight of the depth increments from this core away for radiocarbon dating.

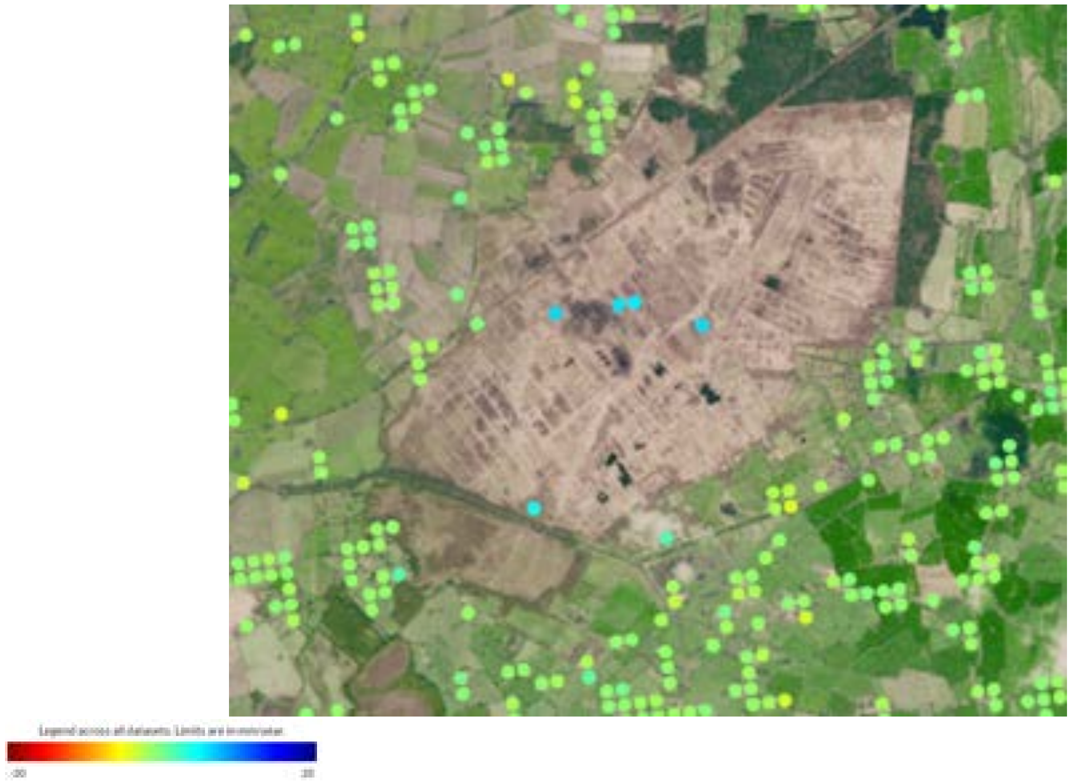


Figure 15. The ground motion across the Mosses as measured from the Sentinel satellites.

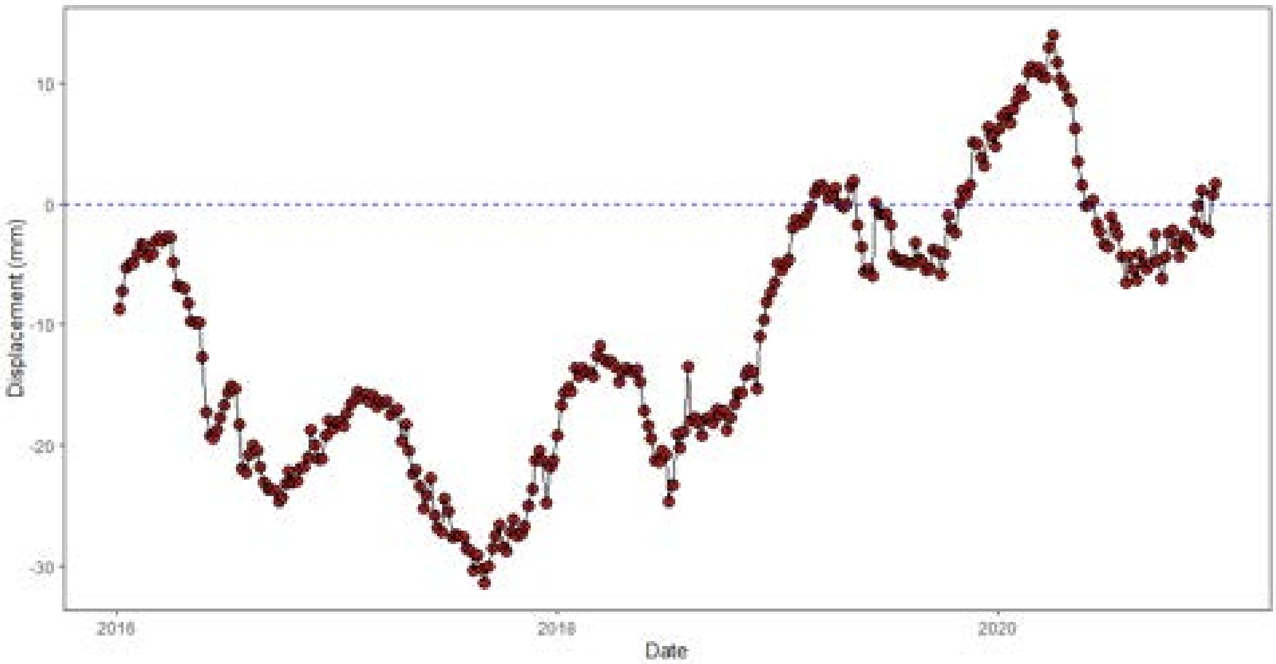


Figure 16. The time series of ground motion for the easternmost of the blue dots within the area of the Mosses shown on Figure 15 (OS National Grid 3468150, 3388150).

5.3) 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 the period of restoration for the Thorne and Hatfield Moors. As an alternative approach it is possible to measure ground motion from satellite. Figure 15 shows the available ground motion data for the Mosses and the surrounding area. The ground motion is given as annual average change since 2016 and suggests that the area around the Mosses has been subsiding (that is the common result for the UK) but, the centre of the Mosses is actually rising. The detail of the ground motion for the centre of the Mosses is shown in Figures 16. A *primo facie* interpretation of this type of data is that peat is accumulating on the Mosses, however, this type of time series can reflect a number of processes not only accumulation, for example, change in water table. Given the hydrology monitoring data already available for the Mosses it would be possible to calibrate the Earth observation data to provide ongoing monitoring of the Mosses.

5.4) Mapping of the C and GHG budgets

The current study has estimated the export of C and GHG under a range of scenarios, i.e. tonnes C or $CO_{2eq}/km^2/yr$, but it has not estimated the actual budgets, i.e. tonnes C or tonnes CO_{2eq}/yr. To make this difference we need to the shapefiles of the management units within the Mosses.

References

Armstrong, H.M., Gordon, I.J., Grant, S.A., Hutchings, N.J., Milne, J.A., and A.R.Sibbald (1997). A model of the grazing of hill vegetation by sheep in the UK .1. The prediction of vegetation biomass. *Journal of Applied Ecology* 34, 1, 166-185.

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

Creevy, A.L., Payne, R.J., Andersen, R. and J.G.Rowson. (2020). Annual gaseous carbon budgets of forest-to-bog restoration sites are strongly determined by vegetation composition. *Science of the Total Environment* 705, Art. No. 135863.

Defra, (2016). Lowland peatland systems in England and Wales – evaluating greenhouse gas fluxes and carbon balances. Final report on project SP1210.

Forrest, G.I., (1971). Structure and Production of North Pennine Blanket Bog Vegetation. *The Journal of Ecology* 59, 2, 453-479.

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., 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.

Worrall, F., Howden, N.J.K., Burt, T.P., Rico-Ramirez, M.A.,and T. Kohler. (2022). Local climate impacts from ongoing restoration of a peatland. *Hydrological Processes* 36, 3, Art. No. e14496.

Appendix 1

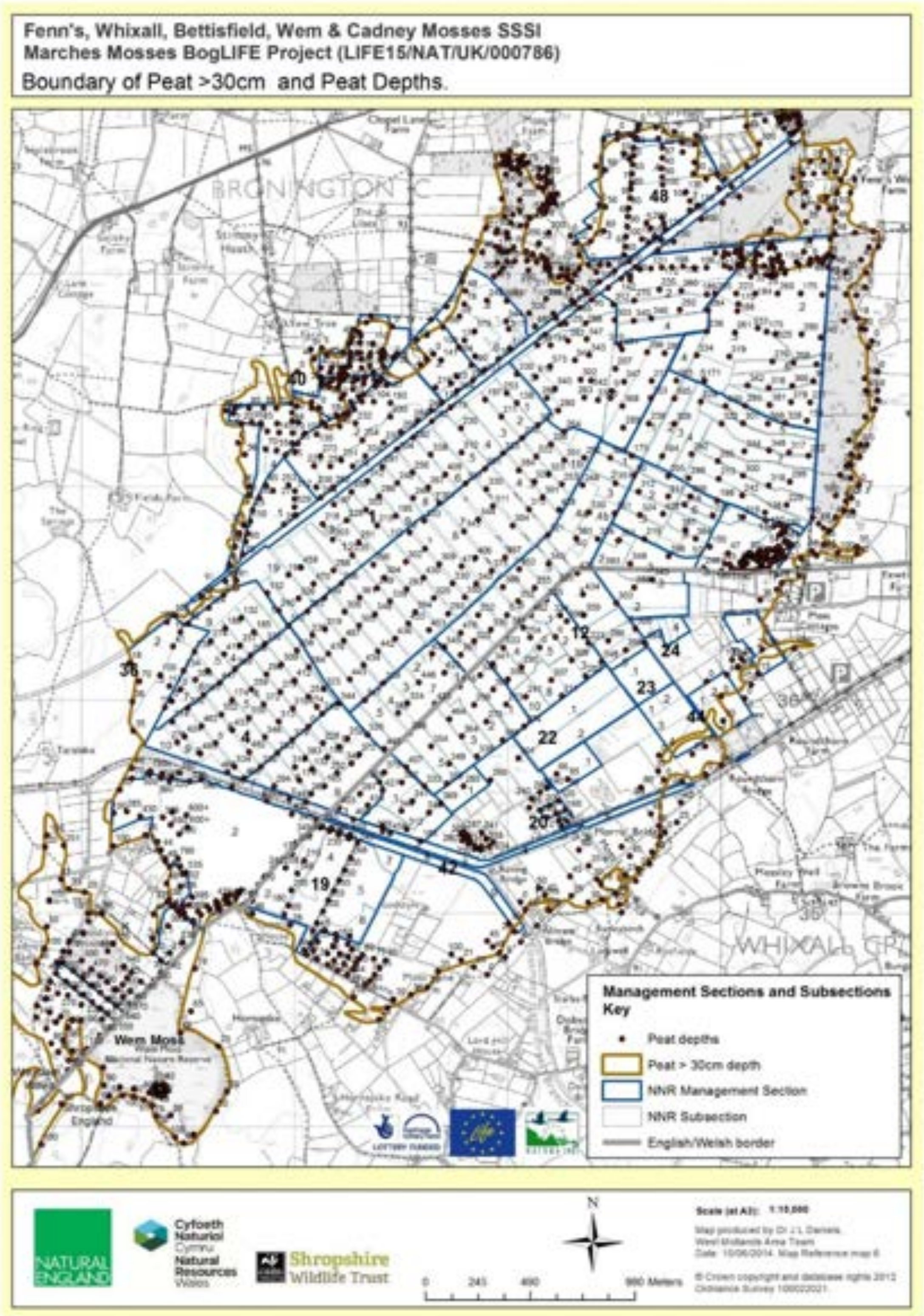


Figure A1. The location of the peat depth measurements used in this study.

Table A1. The C and CO_2 export from the management units of Fenn's and Whixall Mosses based upon a post-LIFE restoration state. The management units are given in Figure 1.

Management unit	Description	Export (tonnes X/km^2/yr)	
		C	CO_2
1	Forestry Clearance and bunding	-128	-502
2	Forestry Clearance and bunding	-125	-495
3	Forestry Clearance and bunding	-124	-496
4	Trees and Scrub - Ex pasture	-128	-462
5	Handcut- Bunded	-130	-444
6	Forestry Clearance and bunding	-125	-490
7	Uncut- Broad leaved removal and bunding	-131	-491
8	Uncut - bunded	-126	-431
9	Trees and scrub	-124	-447
10	Uncut and bunded	-124	-433
11	Grazed	-50	-183
12	Trees and Scrub	-115	-447
13	Handcut- Broadleaved removal and bunding	-125	-494
14	Old commercial - bunded	-122	-429
15	Handcut - bunded	-127	-450
16	Uncut and bunded	-124	-432
17	Old commercial - bunded	-120	-389
18	Handcut -Broadleaved removal and bunding	-130	-489
19	Old commercial - bunded	-128	-391
20	Old commercial - bunded	-126	-391
21	Recent Commercal - Bunded	-123	-333
22	Hand cut	-130	-452
23	Old commercial - bunded	-126	-438
24	Handcut - bunded	-125	-368
25	Handcut	-120	-392
26	Handcut - Broadleaved removal and bunding	-123	-471
27	Handcut	-124	-382
28	Handcut - bunded	-129	-437
29	Handcut - Broadleaved removal and bunding	-127	-474
30	Tree and Scrub	-131	-331
31	Turf Stripped and bunded	-122	-485
32	Handcut - Broadleaved removal and bunding		
33	Turf Stripped and bunded	-131	-516
34	Handcut - Broadleaved removal and bunding	-127	-492
35	Handcut -bunding	-123	-432
36	Handcut -bunding	-126	-433
37	Uncut and bunded	-125	-430
38	Old commercial cutting	-128	-439
39	Uncut and bunded	-131	-397
40	Old commercial - bunded	-128	-417
41	Uncut - Broadleaved removal and bunding	-123	-481
42	Handcut - bunded		
43	Grazed	-87	-319
44	Handcut bunded	-89	-316
45	Handcut	-128	-471

46	Old commercial - bunded	-126	-454
47	Handcut - bunded	-128	-460
48	Old commercial - bunded	-128	-290
49	Handcut- Broadleaved removal and bunding	-129	-437
50	Handcut - Broadleaved removal and bunding	-123	-292
51	Handcut - bunded	-128	-416
52	Tree and Scrub	-122	-442
53	Uncut and bunded	-128	-234
54	Tree and Scrub	-127	-441
55	Handcut - bunded	-130	-388
56	Handcut- Broadleaved removal and bunding	-127	-296
57	Handcut - bunded	-127	-360
58	Uncut and bunded	-129	-294
59	Uncut and bunded	-129	-287
60	Trees and Scrub	-123	-437
61	Lagg restoration	-129	-474
62	Lagg restoration	-129	-511

Table 2. The C and CO_2 export from the management units of Fenn's and Whixall Mosses based upon an optimation scenario. The management units are given in Figure 1.

Management unit	Description	Export (tonnes X/km^2/yr)	
		C	CO_2
1	Forestry Clearance and bunding	-149	-545
2	Forestry Clearance and bunding	-145	-532
3	Forestry Clearance and bunding	-150	-550
4	Trees and Scrub - Ex pasture	-146	-536
5	Handcut- Bunded	-145	-535
6	Forestry Clearance and bunding	-151	-549
7	Uncut- Broad leaved removal and bunding	-150	-550
8	Uncut - bunded	-148	-540
9	Trees and scrub	-146	-542
10	Uncut and bunded	-152	-549
11	Grazed	-150	-547
12	Trees and Scrub	-149	-549
13	Handcut- Broadleaved removal and bunding	-145	-533
14	Old commercial - bunded	-144	-526
15	Handcut - bunded	-146	-539
16	Uncut and bunded	-141	-520
17	Old commercial - bunded	-147	-535
18	Handcut -Broadleaved removal and bunding	-148	-538
19	Old commercial - bunded	-148	-537
20	Old commercial - bunded	-146	-533
21	Recent Commercal - Bunded	-146	-534
22	Hand cut	-148	-544
23	Old commercial - bunded	-149	-543
24	Handcut - bunded	-145	-529
25	Handcut	-150	-548

26	Handcut - Broadleaved removal and bunding	-150	-544
27	Handcut	-152	-552
28	Handcut - bunded	-149	-541
29	Handcut - Broadleaved removal and bunding	-149	-545
30	Tree and Scrub	-151	-548
31	Turf Stripped and bunded	-149	-547
32	Handcut - Broadleaved removal and bunding	-148	-540
33	Turf Stripped and bunded	-147	-535
34	Handcut - Broadleaved removal and bunding	-151	-549
35	Handcut -bunding	-148	-540
36	Handcut -bunding	-149	-549
37	Uncut and bunded	-148	-540
38	Old commercial cutting	-146	-536
39	Uncut and bunded	-148	-537
40	Old commercial - bunded	-149	-548
41	Uncut - Broadleaved removal and bunding	-148	-537
42	Handcut - bunded	-135	-493
43	Grazed	-136	-498
44	Handcut bunded	-134	-491
45	Handcut	-135	-491
46	Old commercial - bunded	-136	-496
47	Handcut - bunded	-135	-497
48	Old commercial - bunded	-133	-486
49	Handcut- Broadleaved removal and bunding	-134	-487
50	Handcut - Broadleaved removal and bunding	-133	-488
51	Handcut - bunded	-134	-490
52	Tree and Scrub	-134	-488
53	Uncut and bunded	-134	-490
54	Tree and Scrub	-133	-487
55	Handcut - bunded	-133	-489
56	Handcut- Broadleaved removal and bunding	-136	-495
57	Handcut - bunded	-134	-490
58	Uncut and bunded	-133	-489
59	Uncut and bunded	-132	-481
60	Trees and Scrub	-138	-503
61	Lagg restoration	-132	-483
62	Lagg restoration	-131	-479

Addendum

Radio Carbon Analysis of 1 metre peat core from Whixall Moss (uncut Cranberry Castle - suspected) arranged by Fred Worrall, Durham University 2023

Core collected as part of field work for **Soil Use and Management, March 2015, 31, 77–88 doi: 10.1111/sum.12155** Estimating the oxidative ratio of UK peats and agricultural soils

	Depth (cms)	**Age (years)**	**C_store**
WHIX C1 0-5	**2.5**	**50**	**1372.775**
WHIX C1 10-15	**12.5**	**433.2064**	**11699.81**
WHIX C1 30-35	**32.5**	**328.7599**	**15769.83**

WHIX C1 50-55	52.5	571.7393	22732.51
WHIX C1 70-75	72.5	863.3375	25880.15
WHIX C1 80-85	82.5	874.078	28346.75
WHIX C1 90-92	91	860.6546	29986.62
WHIX C1 0-5	2.5	50	1091.953
WHIX C1 10-15	12.5	433.2064	8267.607
WHIX C1 30-35	32.5	328.7599	16561.44
WHIX C1 50-55	52.5	571.7393	21633.45
WHIX C1 70-75	72.5	863.3375	25245
WHIX C1 80-85	82.5	874.078	27677.36
WHIX C1 90-92	91	860.6546	29925.44

Whixall – depth-age model

- Peat at 91 cm depth was 861 yrs BP
- Average C budget = 33 gC/m2/yr
- Surface samples were actually modern