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Peatland carbon stocks and burn history: blanket bog peat core evidence highlights charcoal impacts on peat physical properties and long-term carbon storage

Running head: Assessing burn impacts on peat carbon stocks

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Abstract

Peatlands are globally important carbon stores, yet both natural and human impacts can influence peatland carbon accumulation. Whilst changes in climate can alter peatland water tables leading to changes in peat decomposition, managed burning of vegetation has also been claimed to reduce peat accumulation. Particularly in the UK, blanket bog peatlands are rotationally burned to encourage heather re-growth on grouse shooting estates. However, the evidence of burning impacts on peat carbon stocks is very limited and contradictory. We assessed peat carbon accumulation over the last few hundred years in peat cores from three UK blanket bog sites under rotational grouse moor burn management. High resolution (0.5 cm) peat core analysis included dating based on spheroidal carbonaceous particles, determining fire frequency based on macro-charcoal counts and assessing peat properties such as carbon content and bulk density. All sites showed considerable net carbon accumulation during active grouse moor management periods. Averaged over the three sites, burns were more frequent, and carbon accumulation rates were also higher, over the period since 1950 than in the period 1700-1950. Carbon accumulation rates during the periods 1950-2015 and 1700-1850 were greater on the most frequently burnt site which was linked to bulk density and carbon accumulation rates showing a positive relationship with charcoal abundance. Charcoal input from burning was identified as a potentially crucial component in explaining reported differences in burning impacts on peat carbon accumulation, as assessed by carbon fluxes or stocks. Both, direct and indirect charcoal impacts on decomposition processes are discussed to be important factors, namely charcoal production converting otherwise decomposable carbon into an inert carbon pool, increasing peat bulk density, altering peat moisture and possibly negative impacts on soil microbial activity. This study highlights the value of peat core records in understanding management impacts on peat accumulation and carbon storage in peatlands.

Introduction

Globally, peatlands contain ~30% of all soil organic carbon (SOC), despite covering only 3% of the land surface (Parish *et al.*, 2008). In the northern hemisphere circumpolar region it is the generally low temperatures, high water-table depth, high peat moisture, and the resulting slow decay rates of net primary production (NPP), which allow peat to form. Crucially, this slow decay with very limited soil mixing (no meaningful bioturbation or cryoturbation, apart from in permafrost soils) results in annual peat cohorts. The cohorts provide an archive of peatland development (i.e. preserving layered plant and biota remains) alongside pollution traces used for dating such as spheroidal carbonaceous particles (SCPs) that can be used to reconstruct past vegetation, climate conditions and peatland events such as fires over time, providing key information on how peatlands respond to changes in climate and management. Considering the importance of peatlands in the global carbon cycle, it is surprising that global C-coupled climate models still do not adequately represent peatlands (Wu & Roulet, 2014). A better process-level understanding of climate (e.g. Davidson & Janssens, 2006) and management (e.g. Evans *et al.*, 2014) impacts on peatland SOC cycling is clearly needed since the mineralisation of peatland soil organic matter (SOM) has the potential to release vast amounts of previously locked-up C into the atmosphere (as outlined in Heinemeyer *et al.*, 2010, e.g. Yu *et al.*, 2001).

Blanket bogs are a globally rare peatland habitat with the UK accounting for about 15% of the global total (Tallis, 1998). Most peatland sites in the UK are classified as being in a degraded state (Natural England, 2008), partly due to management (e.g. drainage) impacts. In fact, only about 12% of protected blanket bog sites are classified as in favourable condition (Natural England, 2008). In the UK 90% of all peatlands are blanket bogs (Bain *et al*., 2011), which are often managed for grouse shooting, commonly supported by draining the peat and regular burning of vegetation to encourage heather (*Calluna vulgaris*).

Burning on blanket bogs has been highlighted as having potential negative impacts on many of the peatland ecosystem services such as water storage, drinking water quality provision, flood prevention and carbon storage (Evans *et al*., 2014). However, there is only sparse literature on the effects of burn management on actual carbon accumulation rates in blanket bogs (Davies *et al*., 2016). According to Evans *et al*. (2014) there is only one major UK study investigating rotational burn impacts on carbon stocks, and this shows significantly reduced peat carbon accumulation on experimentally burnt compared to unburnt heather dominated blanket bog simulating grouse moor management (Garnett *et al*., 2000). However, the Garnett *et al*. (2000) study contains some potential methodological issues and one study is unlikely to be conclusive, especially from artificial (i.e. experimental) plots. For example, none of the depth profiles in Garnett *et al*. (2000) show the expected spheroidal carbonaceous particles (SCP) peak around 1975, nor do the reported charcoal layers agree with the oldest burn date (i.e. the onset of the experimental burn rotation in 1954 on all plots). Together, these uncertainties mean that the peat C accumulation rates may have been more similar between burnt and unburnt plots than was suggested by Garnett *et al*. (2000). In fact, another study by Ward *et al*. (2007) on the same site as Garnett's study, which was not included by Evans *et al*. (2014), showed equally high C accumulation on burnt and unburnt plots over the top 1 m of peat (based on coarse sampling at 10 cm depth increments). Moreover, the burn plots were artificial (i.e. not part of a real grouse moor), although both offered comparable grazing impacts (see methods) and fairly small (30 m x 30 m). As pointed out by Brown *et al*. (2015), fires on such small experimental areas might not represent real burn rotation impacts (i.e. often burn patches are about 50 m x 100 m and a 10 year burn rotation is considered very frequent). Therefore, a reassessment of this method is urgently required in a real grouse moor context to provide more evidence concerning long-term burn rotation impacts on peat carbon accumulation.

Several peatland models of varying complexity and feedback mechanisms have been developed (Clymo, 1984; Gignac *et al*., 1991; Bauer *et al*., 2003; Frolking *et al*., 2010; Heinemeyer *et al*., 2010; Baird *et al*., 2012), which have often been compared to measured C stocks. However, there is still a surprising lack in both understanding and process level representation of potential management related impacts on peatland SOC cycling and other ecosystem services (Evans *et al*., 2014). Particularly, the evidence in relation to rotational burning as part of grouse moor management is very weak and impacts are often unclear or contradictory (Harper *et al*., 2018). Moreover, the potential of charcoal to 'lock away' carbon over time as suggested by Clay *et al*. (2010) could explain the observed discrepancies in peatland carbon sequestration between flux and stock approaches as highlighted by Ratcliffe *et al*. (2017). Put simply, whilst burning causes considerable loss of above-ground carbon during combustion, it also transforms otherwise decomposable biomass into charcoal, which is very recalcitrant to decomposition (Leifeld *et al*., 2017) and possibly also supresses microbial activity (Lu *et al*., 2014). Although rotational burning on grouse moors is a UK specific issue, the impact of burning and fires on carbon stocks is of global importance as highlighted by the recent findings of charcoal accumulation in drained peatlands with fire history in general (Leifeld *et al*., 2017). However, whilst Leifeld *et al*. (2017) observed a positive relationship between charcoal/SOC ratios and soil depth, they did not include sites with controlled burn rotation management (e.g. grouse moors) nor did they report detailed (i.e. layered) comparisons for bulk density data. Bulk density is a crucial parameter for estimating carbon stocks and also regulates peat hydrology (water holding capacity). Therefore, outstanding yet fundamentally important questions remain regarding controlled burn rotation impacts on long-term peat carbon accumulation in relation to physical properties (i.e. bulk density) and carbon content. Crucially, peat cores can provide the required unique insight into relating peat carbon accumulation and stocks not only to climatic records but also to burn management as past burn events are detectable by charcoal layers alongside changes in peat properties (i.e. bulk density).

Here we conducted a peat core study at three UK grouse moor sites under long-term burn rotation to: (i) reassess previous findings from controlled plot experiments claiming carbon losses by burning (i.e. Garnett *et al.*, 2000) in a real burn management context, and (ii) relate long-term carbon accumulation rates and peat properties (as done by Leifeld *et al.*, 2017) to past burn frequencies. We assessed two hypotheses:

1. Whilst burning decreases soil organic carbon input (loss from litter combustion), it increases bulk density (i.e. higher charcoal content).
2. Peat carbon accumulation relates positively to higher burn frequencies as determined by charcoal layers and largely in relation to increased bulk density.

Materials and Methods

Site locations

The three study sites were all located in north-west England and the names used to identify the sites throughout this report are Nidderdale, Mossdale and Whitendale (Figure 1).

Each site is an actively managed grouse moor with low sheep stocking densities of <0.5 ewes ha^{-1} and offered a rotationally burnt catchment of similar size (~10 ha). The sites were chosen based on a set of key criteria: all were classed as degraded (i.e. heather dominated and past drainage and current burn rotation) blanket bog with a mean peat depth of over 1 m, and were managed as grouse moors. Nidderdale, Mossdale and Whitendale had an average slope at the experimental plots (measured using a 1.5 m long spirit level on a 4 m long wooden plank and representative of the slope across a length of about 50 m) of 3º; 10º; 6º, respectively. Typically, the sites were managed with a 10-15 year burn rotation (based on gamekeeper information) and all had a long history of burning (more than 100 years; based on estate information, most likely burn rotations were part of the management from about 1850 onwards, similar to Moor House as described by Garnett (1998). Figure 2 shows ground-level pictures of all three sites.

All sites had more than 50% ling heather (*Calluna vulgaris*) cover, with at least some existing bog vegetation in the form of cotton-grass (*Eriophorum* spp.) and *Sphagnum* moss species (with most *Sphagnum* spp. cover at Mossdale). National vegetation classification (NVC) categories were determined for each site in 2012 using the MAVIS software (DART Computing & Smart, 2014). Overall, the MAVIS software classified all plots at all sites as the NVC category M19a, which is the *Erica tetralix* sub-community of the *Calluna vulgaris* – *Eriophorum vaginatum* blanket mire community.

Whilst two of the sites had some old and mostly infilled drainage ditches (also called grips) at low density, the third site (Whitendale) without grips included some natural gullies (also mostly revegetated and infilled). The following specific site information was based on a five year (2012-2016) study period (Heinemeyer *et al*. unpublished data) with hourly weather data (MiniMet AWS, Skye Instruments Ltd, Llandrindod Wells, UK), six-hourly readings from water table depth meters (WT-HR 1000, TruTrack, New Zealand) placed inside dipwells in areas of tall heather (last burnt about 15-20 years ago), and manual peat depth assessment in 2012 using commercial (Clarke CHT640) 1.5 cm diameter PVC drainage rods consisting of 92 cm extendable sections with screw fittings (i.e. pushing rods into the peat until detectable resistance of the bedrock/clay layer). The following section provides a basic summary for the three sites including climatic, hydrological and soil conditions and locations are shown in Figure 1.

Nidderdale is located on the Middlesmoor estate in upper Nidderdale, which lies within the Yorkshire Dales National Park, UK, at 54°10’07”N; 1°55’02”W (UK Grid Ref SE055747) about 450 m a.s.l. The site had a mean annual air temperature of 7.2 ± 0.5°C and annual precipitation of 1587 ± 211 mm. The mean annual water table depth was -14.6 ± 6.4 cm. The soil is a poorly draining organic peat (Winter Hill series) with an average depth of 1.6 ± 0.3 m across the experimental plot; peat depth across the catchments ranged from 0.2 m to 2.9 m. Most of the grips within the study area, which were dug about 40 years ago, were naturally infilled by 2010 and no further grip blocking took place during the study period.

Mossdale is located in Upper Wensleydale within the Yorkshire Dales National Park at 54°19’01”N; 2°17’18”W (UK Grid Ref SD813913) about 390 m a.s.l. The mean annual air temperature was 7.2 ± 0.5°C and annual precipitation was 2029 ± 346 mm. The mean annual water table depth was -8.1 ± 5.7 cm. The soil is a poorly draining organic peat (Winter Hill series) with an average peat depth of 1.2 ± 0.4 m at the experimental plot; peat depth across the catchments ranged from 0.3 m to 2.1 m. Most of the grips within the study area, which were dug about 40 years ago, were naturally infilled by 2010.

Whitendale is located within the Forest of Bowland (an Area of Outstanding Natural Beauty; AONB), Lancashire, at 53°59’04”N; 2°30’03”W (UK Grid Ref SD672543) about 410 m a.s.l. The mean annual air temperature was 7.6 ± 0.5°C and annual precipitation was 1858 ± 308 mm during the five year study period. The mean annual water table depth was -8.7 ± 6.9 cm. The soil is a poorly draining organic peat in the Winter Hill series with an average peat depth of 1.7 ± 0.4 m at the experimental plot; peat depth across the entire catchment area ranged from 0.2 m to 4.5 m. This study area had no grips, although gullies (similar to grips but naturally formed) were present in both catchments.

Peat sampling

Peat samples were taken using a manual 1.1 m box corer. At all three sites, 1 m depth (5 x 5 cm diameter) peat cores were taken twice after burning in March 2013 from within a 5 m radius near one experimental burn plot, two adjacent ones (within 0.5 m) in early April 2016 (set 1) and one in late March 2017 (set 2) to supplement peat property data. Peat cores were transferred in the field into a three-sided square ducting and contained by the cover lid for transport to cold storage in a fridge and then freezer. The top 25 cm of the peat profile was analysed for dating and peat property analysis, specifically carbon content (C_{org}), bulk density (BD), and macro charcoal fragments (>120 µm particle size).

Peat core dating

Peat core dating was done (for both cores from set 1) based on counting spheroidal carbonaceous particles (SCPs) and relating it to the onset of fossil fuel driven industry and the onset of clean air technology resulting in a peak shaped SCP distribution (e.g. Swindles, 2010).

Spheroidal Carbonaceous Particles (SCPs) were analysed according to Swindles (2010) with some adaptations (as outlined below) due to the specific nature of the peat. Contiguous 2 cm^3 subsamples of the paired peat cores from each site were taken to a depth of 16 cm (below the depth of SCP onset for all sites) at 0.5 cm resolution. A saw and a chisel were used to sample from the frozen cores and the dimensions of the resulting gap (e.g. for volume determination) were measured with a Vernier calliper (see De Vleeschouwer *et al*. 2010). The samples were dried overnight at 105 ºC and 0.1 g of dried sample was then prepared using an acid digestion in 30 ml of concentrated nitric acid (HNO_3), which was left for 24 hours at room temperature before being put on a hot plate at 140 ºC for up to 10 hours (until the solution was reduced to approximately 5 ml and all organic material had dissolved). Subsequently 10 ml of deionised water was added and the suspension was transferred to a 15 ml polypropylene centrifuge tube for centrifuging at 1500 r.p.m. for five minutes. The supernatant was decanted into a sink and the residue was washed twice more with deionised water, centrifuged and the supernatant decanted. The final residue (~15 ml or less) was decanted into a small centrifuge tube and as much water as possible was removed using a Pasteur pipette (the remaining sample weight was determined). A small quantity of the liquid residue (a drop) was removed and placed on a coverslip (the remaining sample residue was weighted again to determine the actual sample weight analysed for SCPs). The coverslip was left in a fume hood overnight to evaporate all water. A known quantity of the final solution was mounted on 22 mm rectangular slides using Histomount. SCPs were counted under a light microscope at x400 magnification and expressed as # gDM^{-1} (i.e. number of particles per gram of dry mass of peat) according to Swindles (2010). SCPs of approximately 2 microns and larger were identified based on their spheroidal three-dimensional morphology (determined by focusing in and out on the particle using a light microscope) and distinctive black colour. SCP particles are usually between 10 and 70 μm in diameter and may have a pitted or lacy surface texture (Swindles, 2010). The trace of SCPs in the cores from this study was undetectable below a depth 15 cm.

Peat property analyses

Carbon content

Two carbon content (C_{org}) datasets were used (set 1 & 2). C_{org} for individual (0.5 cm) peat layers was measured for subsample sections on 0.5 cm x 4 cm dried section removed for BD assessment (see below) from each layer (set 1: 0-15.5 cm; set 2 16-25 cm). Dried peat samples were manually ground up in a mortar. For each analysis, about 30 mg of the ground samples was sealed in pre-weighed tin foil capsules and run through a vario Macro C/N analyser (Elementar Analysensysteme GmbH, Hanau, Germany) according to a standard operating procedure ('Plant500'; Environment Department, University of York). Results were factored to glutamic acid standards and compared to organic material standards (i.e. blanks are empty compartments in the carousel; glutamic acid of 50 mg (± 0.5) provide a 'daily factor' and are used to adjust the results of several daily runs against each other; a reference material of birch leaf was used at the start and end of the run (Elemental Microanalysis Ltd CatNo. B2166, C_{org} 48.09% +/- 0.51%, N 2.12% +/- 0.06%).

Bulk density

To determine BD, 2 cm^3 contiguous subsamples at 0.5 cm resolution (set 1 & 2 as above) were cut from the cores from each site to a depth of 25 cm. A knife was used to sample sections from the fresh cores (which were waterlogged) and the volume of each section was measured by water displacement in a 20 ml measuring cylinder. Samples were dried at 105ºC in 10-30 ml crucibles for a minimum of 48 hours. All peat samples were dried until a constant weight was reached and stored in a desiccator until further analysis. BD was calculated as g dry matter per cm^3.

Macro-charcoal analysis

Peat cores (set 1) for each site (Nidderdale, Mossdale and Whitendale) were analysed for macro-charcoal content following the sieving method described by Mooney & Tinner (2011). Two cores were analysed for Nidderdale, an initial 'test core', and a primary core. As both cores showed similar results, charcoal counts were averaged between the two. Contiguous 2 cm^3 subsamples at 0.5 cm resolution to a depth of 25 cm were left in a 10-15% solution of hydrogen peroxide (H_2O_2) for a minimum of 24 hours in order to bleach the organic matter allowing for counting of the charcoal particles which remain unchanged by the H_2O_2. Bleached samples were gently washed through nested sieves of two mesh sizes to capture two size fractions (>120 µm and >500 µm) of charcoal particles. These were counted separately on a petri dish with a coarse grid under a light microscope at x20 magnification.

Burn frequency estimates

Past fire frequencies were based on identifiable charcoal peaks per time period responding to grouse shooting intensity (most intense: 1950-2015; less intense: 1850-1950; pre driven shoots: 1700-1850). For this, the latest surface burn layer marked 2013 for all sites, the SCP dating (defined by the average of set 1 for SCP peaks, their onset and decline) was used to obtain a site specific depth corresponding to the years 1975, 1950 and 1850 (as per Swindles, 2010) and the year 1700 was assumed to be the same for all three sites (25 cm peat depth) based on dating a very similar blanket bog with similar peat depth and at similar altitude at Moor House (based on unpublished data provided by Graeme Swindles at the University of Leeds and also the unpublished PhD thesis by Garnett, 1998). Therefore, the oldest age was the most uncertain as it had to be assumed that past accumulation rates were similar across the three sites (which is likely as none of the sites were intentionally managed for grouse before 1850). If a charcoal peak occurred at an age threshold, it was counted only in the upper layer (as charcoal infiltration would have most likely resulted in a downward migration).

Peat and carbon accumulation rates and carbon stocks

Peat accumulation across the peat profile was calculated by using the peat depth increments (over time as derived by the SCP dating method). Carbon stocks were derived by multiplying C_{org} with the BD of the corresponding peat depth section (and adding up over depth layers); this used individual 0.5 cm sections. For carbon accumulation rates carbon stocks per depth layer were divided by the SCP identified time periods in years (see burn frequency method section above).

Statistical Analyses

All statistical analysis was performed in R (R Core Team, 2016). Differences in carbon stocks between the sites (3) were analysed using one-way ANOVA and Kruskal-Wallis H tests (as the data did not fulfil the ANOVA criteria of a normal distribution). Differences in carbon accumulation rates were analysed using two-way ANOVA and Friedman tests (as the data did not fulfil the Levene's test for equality of error variances as ANOVA criteria), with data grouped into three periods defined by the onset and decline of SCPs and maximum core depth. Linear regressions were performed for the peat chemical and physical parameters against natural log transformed charcoal count data. The adjusted coefficient of determination (Adj. R^2) is reported, which corresponds to adjustments made to the R^2 based on the degrees of freedom of the respective model (adjusted to the number of regressors and the sample size).

Results

The patterns in BD, SCPs and C_{org} were similar for all three sites (Figure 3). There was a peak in BD of around 0.15-0.2 g cm^{-3} at a depth of about 5 cm, which coincided with the highest peak in SCPs at all sites. The C_{org} showed a general increase with depth from about 53% to around 56%, but this was separated by a sudden shift at around 10 cm depth (which coincided with the SCP peak areas), where a decrease from the surface to bottom peat layers in C_{org} of about 5% was observed (Figure 3). The BD, SCP counts and C_{org} were lowest overall at Mossdale, and the SCP peaks at Mossdale and Whitendale were at 6 cm compared to 4 cm at Nidderdale. SCPs could not be detected below 14.5 cm at Mossdale, 13 cm at Nidderdale and 14 cm at Whitendale.

The layered BD, C_{org} and peat-age profile data (Figure 3) allowed calculation of C accumulation rates over time (Figure 4). Mean C accumulation rates (in gC m^{-2} yr^{-1} ± standard deviation) over the entire top 26 cm (equal to the period 1700-2015) increased in the order Mossdale (46 ± 22), Nidderdale (50 ± 24) and Whitendale (68 ± 37).

There were clear peaks in charcoal concentration throughout the peat profile. However, peaks were larger and more frequent nearer the surface, particularly for Nidderdale and Whitendale (Figure 5).

Together with the SCP-based dating tool and the estimated age of 1700 at the maximum peat depth, the charcoal peaks (size fraction >120 µm) provided estimates of past burn frequencies (Table 1). Burn frequencies were shortest on average during the period 1950-2015 (every 17 years; 1850-1950: every 28 years; 1700-1850: every 31 years) and burns were most frequent, when averaged over the whole period since 1700, at Whitendale (every 23 years), less frequent at Nidderdale (every 25 years) and least frequent at Mossdale (every 28 years). However, the actual charcoal peaks were highest at Whitendale and Nidderdale, with very low counts for the Mossdale site during 1850-1950 (cf. Figure 5); thus burn frequencies (and possibly intensity) for Mossdale might be less in comparison to the other two sites than the 25 years indicated for the period 1850-1950 in Table 1 as this was based on very low charcoal counts per peak.

Carbon accumulation rates were not normally distributed but both, parametric and non-parametric tests on the natural log transformed data resulted in the same statistical differences (only the non-parametric results are reported). The carbon accumulation rates (mean ± standard deviation), based on BD and C_{org} for the individual, management related SCP dated sections (Figure 6), were significantly ($p<0.001$) higher (87 ± 32 g C m^{-2} yr^{-1}) during the most recent period (1950-2015) compared to 1850-1950 (38 ± 11 g C m^{-2} yr^{-1}) and 1750-1850 (43 ± 8 g C m^{-2} yr^{-1}). Whilst the carbon accumulation rates in the two most recent periods were significantly higher ($p = 0.001$) at Whitendale than at Mossdale or Nidderdale, rates were significantly higher ($p < 0.001$) at both Nidderdale and Whitendale than at Mossdale during the oldest period.

The peat core analysis revealed several positive relationships in the chemical and physical peat properties and the charcoal concentration, which were consistent between sites, but the regressions became less robust (the margin of statistical uncertainty was larger) when using fewer data (i.e. going from all sites to individual sites and from the entire 25 cm core to only the top 15 cm layer). However, all peat and peat carbon accumulation rates showed strong multimodal distributions and thus the linear regression analyses lose some statistical robustness and the below data and regression results are mainly reported to offer a comparison to other studies.

Over the top 15 cm, the three sites revealed significant (see Table 2) correlations between BD, C_{org}, peat and carbon accumulation rates and natural log transformed charcoal concentrations (Figure 7). Importantly, the greatest impact overall was observed for BD (Figure 7A; Table 2), which reflected the strong relationships at the overall most frequently burnt sites with higher charcoal counts at Nidderdale and Whitendale (Figure 7B). However, whereas BD and C accumulation rates showed a fairly strong (Adj. R^2 of ~0.4) positive relationship with charcoal piece abundance, C_{org} showed a generally very weak (Adj. R^2 of ~0.1) positive relationship. Moreover, the R^2 values for the various regressions against the natural log transformed charcoal concentrations were overall highest for Nidderdale (see Table 2). Most likely this improved regression fit was related to a clearer peak distribution due to more charcoal (i.e. higher counts) with overall well defined burn peaks (Figure 5). Moreover, this high Nidderdale charcoal count possibly reflected the drier climate conditions (i.e. Nidderdale generally providing the best heather burning conditions due to lowest rainfall of all three sites, see methods section).

Over the entire peat depth (25 cm), the three sites also revealed significant (see Table 3) correlations between BD, peat and carbon accumulation rates and charcoal concentrations but not for C_{org}. Again, the greatest impact (greater BD; Figure 8A) occurred on the overall most frequently burnt sites Nidderdale and Whitendale (Figure 8B). As observed for the top layer, BD and C accumulation rates showed an overall strong positive relationship (Adj. R^2 ~0.35) with charcoal piece abundance, whereas peat accumulation showed only a weak positive relationship (Adj. R^2 ~0.16) and C_{org} did not reveal any relationship (see Table 3). Moreover, the R^2 values for the natural log transformed charcoal regressions (for carbon, peat accumulation and BD), were again highest for Nidderdale (see Table 3), possibly relating to the overall high burn frequency (Table 1) and charcoal concentrations (Figure 5).

Discussion

Effects of rotational burning on heather-dominated peatlands is still a controversial issue, partly due to uncertainties around the claims of negative impacts on key ecosystem services such as water quality and carbon storage (Harper *et al.*, 2018). This study provided novel insights into ecological applications of peat core-derived burn frequency reconstructions in a real grouse moors management context. The findings highlight the value of paleo-ecological records to allow better understanding of the effects of management on peat development as done previously by Mackay & Tallis (1996), C cycling and storage. Of particular interest is the new fine scale age-cohort information on peat properties and charcoal content in relation to carbon accumulation. As highlighted by Leifeld *et al.* (2017) for fire impacts on pyrogenic carbon content and C storage in northern peatlands, this fine detail on ecosystem charcoal inputs provided novel insights into potential positive long-term burn management impacts on soil carbon storage. However, although the present study reports findings for blanket bog peatlands, the general link between fire impacting carbon storage via peat properties and pyrogenic carbon (i.e. charcoal) is of general concern; nearly all biomes burn naturally over longer time scales (in the order of several decades to a few centuries as shown for boreal forests by Kelly *et al.*, 2016 and also summarised for peatlands by Leifeld *et al.*, 2017) and many areas under agricultural cultivation are burnt intentionally. However, the functional role of charcoal is still little understood (Pingree & DeLuca, 2017) and SOC models do not include the here observed burning impacts on soil properties (i.e. bulk density), C compounds (i.e. charcoal) and thus long-term C storage. Moreover, our findings highlight that these changes have potentially important implications on C cycling via eco-hydrological feedbacks, for example on water holding capacity due to changes in BD, but also via soil biota, potentially affecting microbial communities and decomposer activity (Lehmann *et al.*, 2011) due to so far unknown interactions.

Burning causes gaseous N-losses from combustion, which could have reduced N-availability in the soil organic matter (SOM) and may explain the observed increase with depth in peat C_{org} (Figure 3). However, the positive charcoal effect on C_{org} was very weak for the top 15 cm and disappeared in the overall core analysis. Possibly the weaker overall C_{org} relationship with charcoal reflected an increasingly difficult direct link between the two parameters with depth (and thus time), as they were measured in two separate samples. The increased BD observed at the more frequently burnt sites Nidderdale and Whitendale (supporting hypothesis 1) likely reflected charcoal and ash particles filling the peat pore space. This change in soil chemical and physical peat properties (i.e. increased BD) resulted in the observed higher C accumulation rates at the more frequently burnt sites overall (supporting hypothesis 2) (Figure 4) and over the three management related periods (Figure 6). In fact, mean C accumulation rates (2015-1950) of 3.2 t CO_2 ha^{-1} yr^{-1} (87 g C m^{-2} yr^{-1}) were very similar to the 3.8 t CO_2 ha^{-1} yr^{-1} as reported previously by Evans *et al*. (2014) for unburnt management based on data presented by Garnett *et al*. (2000). This was unexpected as, so far, one major plot-level study assessing burn rotation effects on peat C accumulation rates found a considerable carbon loss of -1.1 t CO_2 ha^{-1} yr^{-1} under burning over a similar time period (cf. supplementary material in Evans *et al*. (2014) based on data by Garnett *et al*. (2000)). However, alongside Clay *et al*. (2010), we note some potential methodological issues in the Garnett *et al*. (2000) study: BD samples were only dried for only 24 hours, C_{org} was assumed to have a constant value of 50%, and SCP preparation methods could have hindered particle identification. In addition, their reported charcoal layers did not agree with the oldest burn date (i.e. the onset of the experimental burn rotation in 1954 on all plots; cf. Figure 3 in Garnett *et al*., 2000). In fact, none of the depth profiles in Garnett *et al*. (2000) show the expected SCP peak around 1975, but all show a clear and high charcoal peak at about 10-11 cm depth. Notably, Garnett *et al*. (2000) did not consider this disagreement between SCP and charcoal dates in their age-depth determination, although the charcoal peak at 10-11 cm most likely indicated the year 1954 (i.e. the onset of the experiment). Together, these uncertainties mean that the peat C accumulation rates may have been more similar between burnt and unburnt plots than was suggested by Garnett *et al*. (2000).

The disagreement between burn frequencies (Table 1) and C accumulation (Figure 6) in the mid period (1950-1850) for Mossdale versus Whitendale could reflect methodological challenges; as charcoal concentrations were very low for Mossdale in older than 1850 layers

(Figure 5), and depth layers are also closer together (thinner), so accurate charcoal peak detection and separation as well as dating became less reliable. Ideally larger peat volumes should be considered for charcoal extractions and ^{14}C or lead isotopes could be deployed to resolve the age resolution, although the reliability of the radiocarbon method becomes limited nearer the peat surface (e.g. Garnett, 1998) and lead isotopes can be unreliable in peat, partly due to plant-derived isotope inputs (e.g. Olid et al., 2008)). The lower but still relatively high fire frequencies of every 31 years (across all sites) before the intensification of grouse shooting (Table 1) could indicate that rotational burning was already used to encourage livestock grazing (but no data are available in this respect). However, for the Forest of Bowland (Whitendale), past high fire frequency has previously also been indicated by high and frequent charcoal counts (Mackay & Tallis, 1996).

A comparison of the peat C accumulation rates reported here to published data from other peatland sites over corresponding time periods (see Table 4) revealed very good agreement, particularly when comparing this study to other blanket bog studies (Billett *et al.*, 2010; Garnett, 1998; Hardie *et al.*, 2007). Carbon accumulation rates in these studies are generally much higher during the most recent periods (about 50 - 100 g C m^{-2} yr^{-1}), reflecting highly undecomposed peat, whereas long-term accumulation rates for older layers are about 30 g C m^{-2} yr^{-1}. Notwithstanding the overall good agreement in accumulation rates, slope impacts on peat depth and C accumulation (see Heinemeyer et al., 2010) are often ignored. However, slopes of 3-10 degrees in our study are likely comparable in relation to the Garnett *et al.* (2000) study describing it as a “gentle” slope (in agreement with the figure provided in Garnett’s (1998) thesis [i.e. Plate 4.1, page 90]), implying a slope of around 5-10 degrees). We also acknowledge that burnt areas are located within their own topography and greater slopes than in this study could possibly lead to high erosion, particularly under a very frequent burn rotation.

All three sites showed a long burn history. The more frequently burnt and more modified (e.g. drier with lower water tables and less *Sphagnum* spp. moss cover) sites Nidderdale and Whitendale showed higher C accumulation overall (Figure 4). Whilst both sites also showed higher C accumulation than Mossdale in the oldest period (1700-1850), Whitendale was also highest in the other two periods (Figure 6). However, the least modified (e.g. wetter with higher water tables and most *Sphagnum* cover) site Mossdale showed less C accumulation (although burn frequency was equally high for Mossdale and Whitendale during 1850-1950; Table 1). Three processes could explain this: (1) burning converted otherwise decomposable heather biomass carbon into 'inert' charcoal (about 5% of standing heather biomass equal to ~18 g C m^{-2} of charcoal, Heinemeyer *et al*., unpublished, but similar to estimates by Worrall *et al*. (2011) of 6.4 g C m^{-2}) or as reported in Clay and Worrall (2011) as 4.3% (of the biomass consumed) in a wildfire, (2) the bulk density increased, possibly due to incorporation of ash and charcoal fragments thus increasing C stocks, and (3) a potential negative priming effect on decomposition by charcoal (Lu *et al*., 2014). Notably, this also agreed with the lower C accumulation rates at Nidderdale during 1850-1950 (Figure 6), a period which showed reduced burn frequencies (Table 1) and overall low charcoal counts (Figure 5) at this site. However, the currently anticipated concept that burning over time leads to a decline in peat C stocks, which is largely based on one peatland study (i.e. Garnett *et al*., 2000; and in parts Ward *et al*. (2007) for the same experimental plots) as highlighted by Evans *et al*. (2014), does not agree with this study, which observed considerable C accumulation during grouse moor management periods (Figure 6) which was also positively related to burn frequencies (Table 1).

However, the conclusions reached here are based on a C-stock inventory which could be different when compared to using a C-flux approach. Indeed such discrepancies between flux and stock approaches in determining ecosystem C accumulation rates for peatlands have been highlighted previously by Ratcliffe *et al*. (2017) and Clay *et al*. (2010). The major disadvantages of the C-flux approach are that it does not capture long-term incorporation of carbon as charcoal (Clay *et al*., 2010), whilst capturing decomposition from deeper, older layers, which affects the C budget calculations of recent periods, due to the mixed age of the overall decomposition signal. The major disadvantages of the C-stock approach are that it relies on uncertain dating techniques (particularly when using only one dating tool, such as SCPs, as in our study) and considers sections of peat separately, which ignores incorporation of surface carbon into deeper sections through roots and changes in decomposition rates over time. These methodological uncertainties and discrepancies between these approaches require further research in order to obtain greater confidence in long-term ecosystem carbon sequestration rates in relation to both climate and management, particularly in peatlands. We also acknowledge that our findings were based on several cores albeit from the same locations. Ideally larger cores would be utilised, enabling all analyses to be done on the same core.

Conclusion

In conclusion, this study supports the hypotheses that increased charcoal input in relation to past burn frequencies can increase peat long-term SOC accumulation. This highlighted the potential of increased long-term C sequestration on rotationally burnt peatlands, possibly due to BD changes, and revealed implications in relation to discrepancies between the flux and stock approaches in peat carbon sequestration. However, while the methods of dating using SCPs and sieving for charcoal are validated methods, the authors recognise the uncertainties associated with these methods. Other factors may have also influenced the findings regarding charcoal impacts on C accumulation in relation to burn frequency (e.g. changes in N or vegetation composition and thus litter quality). Moreover, the current study was conducted on fairly flat areas (<5°), excluding steeper slope areas, where erosion on bare ground following burning could result in major C losses. Finally, our results do not allow a comparison to an unburnt scenario and estimates are based on low severity prescribed burns and the impacts of more severe arson or wildfire are likely to differ (i.e. when peat burning occurs), leading to considerable peat depth and thus C loss (e.g. Mackay & Tallis, 1996). Notwithstanding these uncertainties, this study highlights the importance of understanding fire dynamics for SOC dynamics and ecosystem C storage and the need to improve our scientific understanding of the processes and their historical importance to the carbon cycle. Therefore we suggest that further study using advanced techniques, such as carbon dating and core scanning (e.g. X-ray fluorescence (XRF) and X-ray computer tomography (CT)), is crucial, especially to further develop carbon assessment methods and models. Further research is also needed to assess the wider landscape scale (i.e. topographic range) impact of increased charcoal and ash incorporation on peat hydrology and the potential eco-hydrological feedbacks on decomposition processes, as recently highlighted by Ratcliffe *et al.* (2017), in addition to potential microbial feedbacks. Finally, any holistic burn impact assessment should ideally be providing comprehensive assessments including above-ground, hydrological, gaseous and below-ground parameters in estimating catchment carbon stocks/fluxes (specifically considering the above outlined methodological and topographic limitations in this study).

Acknowledgements

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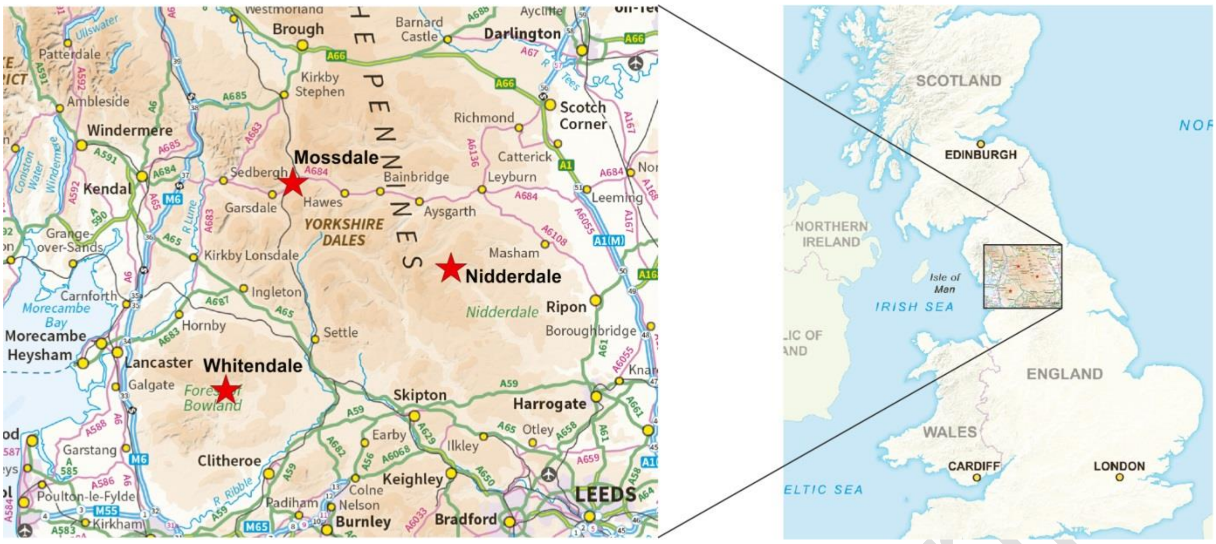


Figure 1: Field site locations in north-west England (inset) in relation to the United Kingdom (outline). Shown are the three sites Nidderdale, Mossdale and Whitendale (indicated by the red stars). Maps downloaded: 09th September 2016 from MiniScale® [TIFF geospatial data] during download of GB tiles (updated 3rd December 2015) from Ordnance Survey (GB) using the EDINA Digimap Ordnance Survey Service (http://digimap.edina.ac.uk).

Figure 2: Site conditions as observed by ground-level pictures (credit A. Heinemeyer) taken in winter 2012 at each site (Nidderdale, Mossdale and Whitendale). Note the burn areas with regrowing sedge cover (mostly cotton-grass (*Eriophorum* spp.)) on the otherwise heather-dominated blanket bog vegetation.

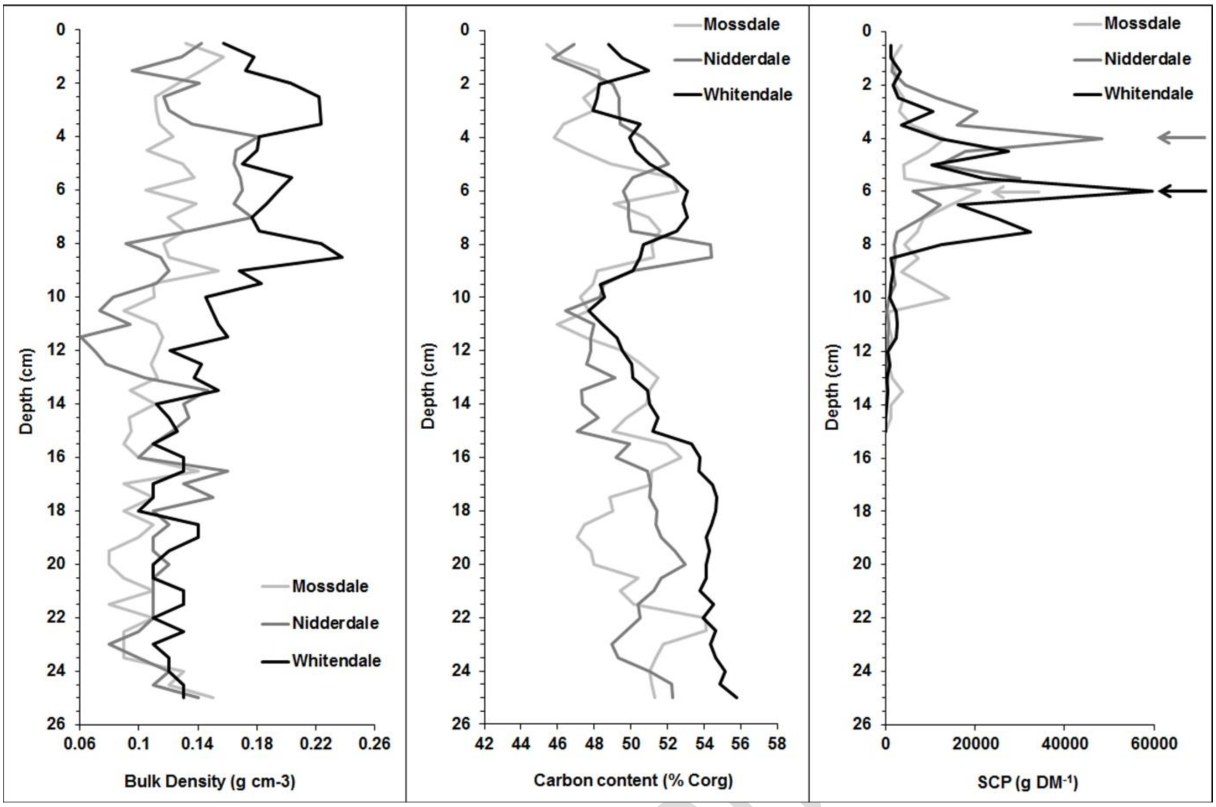


Figure 3: Peat core depth profile for bulk density (left), carbon content (%C_{org}) (middle) and spheroidal carbonaceous particle (SCP) counts (right) for the three sites determined in 0.5 cm sections to a depth of 25 cm (note the different y-axis for SCPs as these were only detected to 15 cm depth) with arrows indicating the peak SCP counts corresponding to the year 1975 (as per Swindles, 2010).

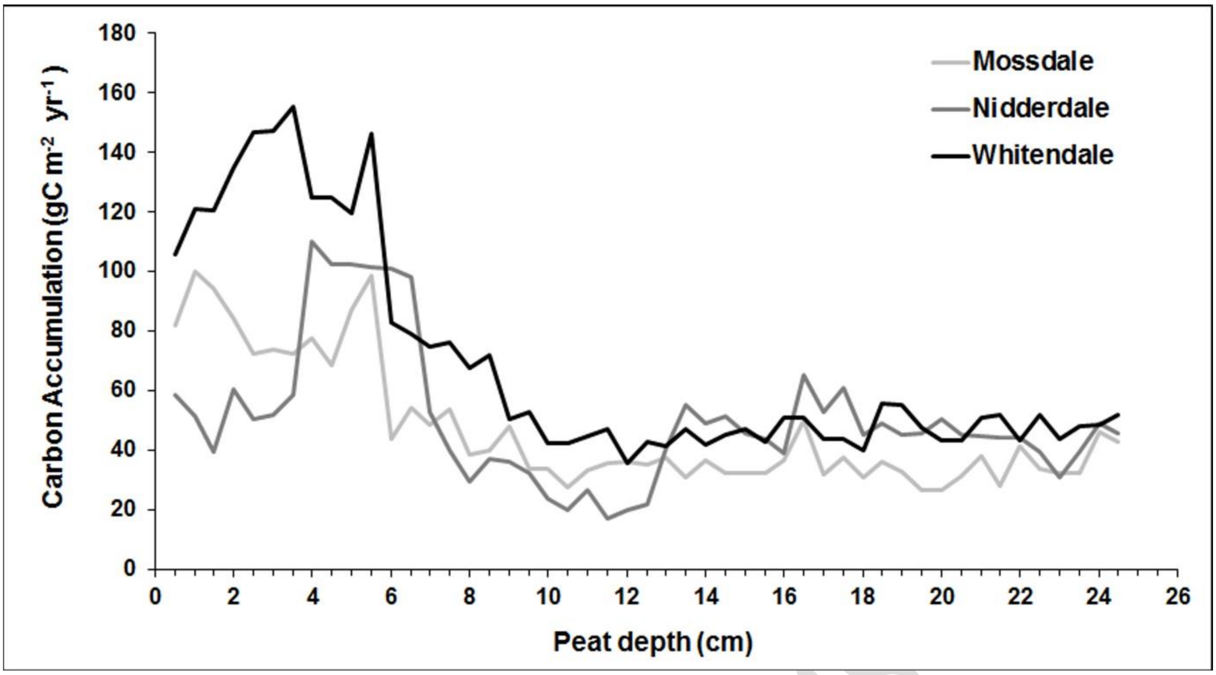


Figure 4: Annual peat carbon (C) accumulation rates derived from data in Figure 3 (i.e. bulk density, C content and spheroidal carbonaceous particle (SCP) age-depth profile data) for the three sites.

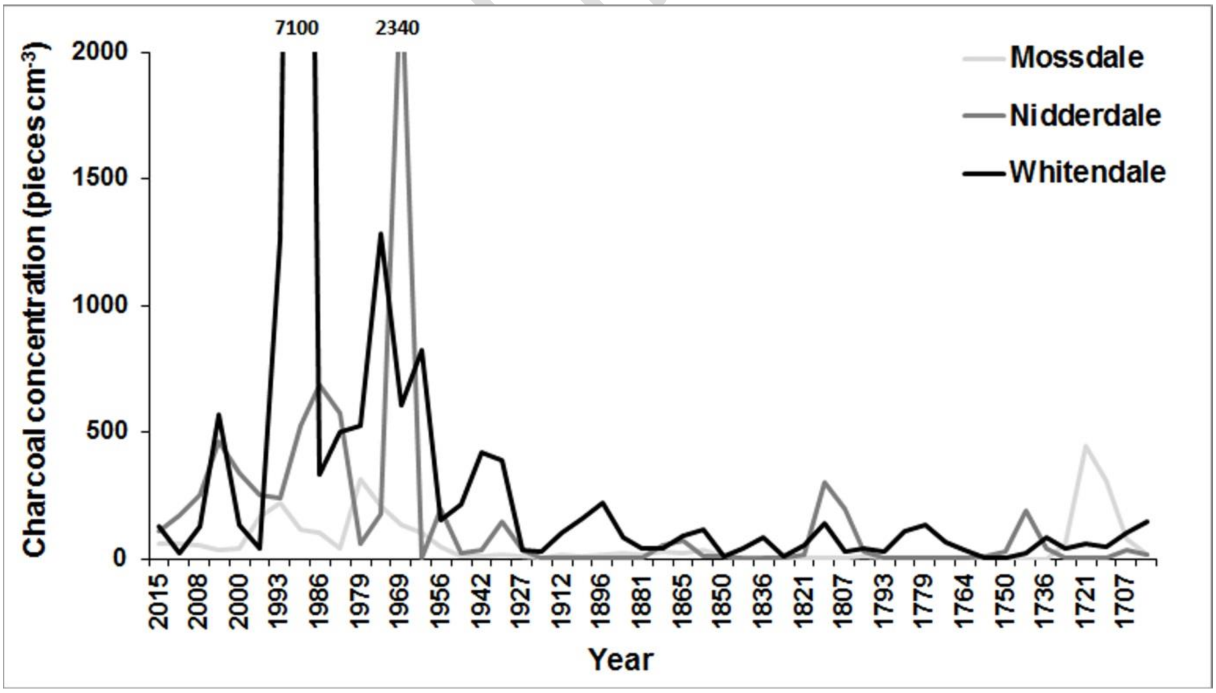


Figure 5: Charcoal concentrations (with a size fraction of >120 µm) through the peat core depth profile for the three sites, determined for each 0.5 cm section to a depth of 25 cm but shown as the year each depth relates to (based on spheroidal carbonaceous particle (SCP) peat

core dating over the top 15 cm and assuming an age of 1700 at 25 cm based on data by Garnett, 1998)). The y-axis is truncated to allow peak identification (the maximum values are given where peaks are cut off).

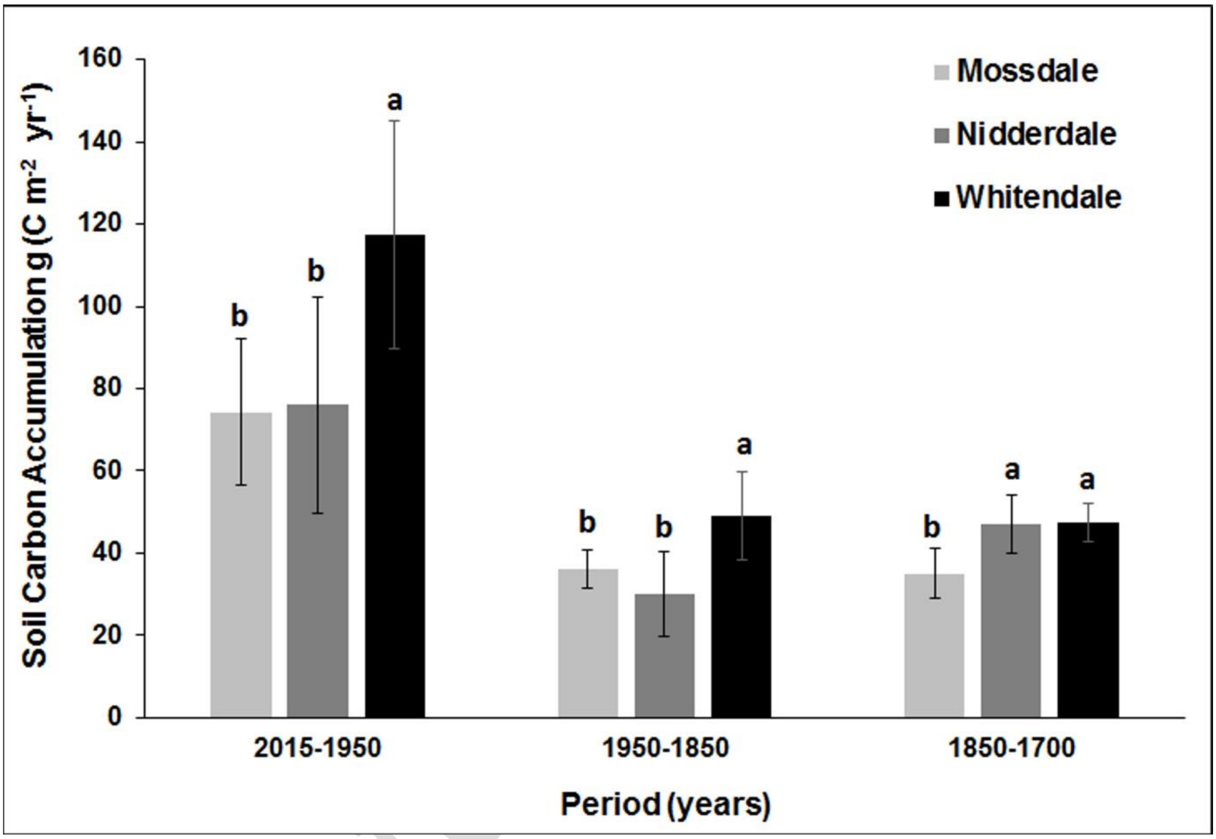


Figure 6: Soil carbon accumulation rates, based on spheroidal carbonaceous particle (SCP) dating of the peat cores together with detailed bulk density and organic carbon content from the 0.5 cm peat depth layers. Mean (± standard deviation) rates were calculated for each site for separate periods, reflecting approximate times of management changes (i.e. onset of grouse moor management in 1850 and intensification from 1950). Accumulation rates differed significantly (indicated by different letters for each period) between sites in all three periods (2015-1950: $p = 0.001$; 1950-1850: $p< 0.001$; 1850-1700: $p< 0.001$).

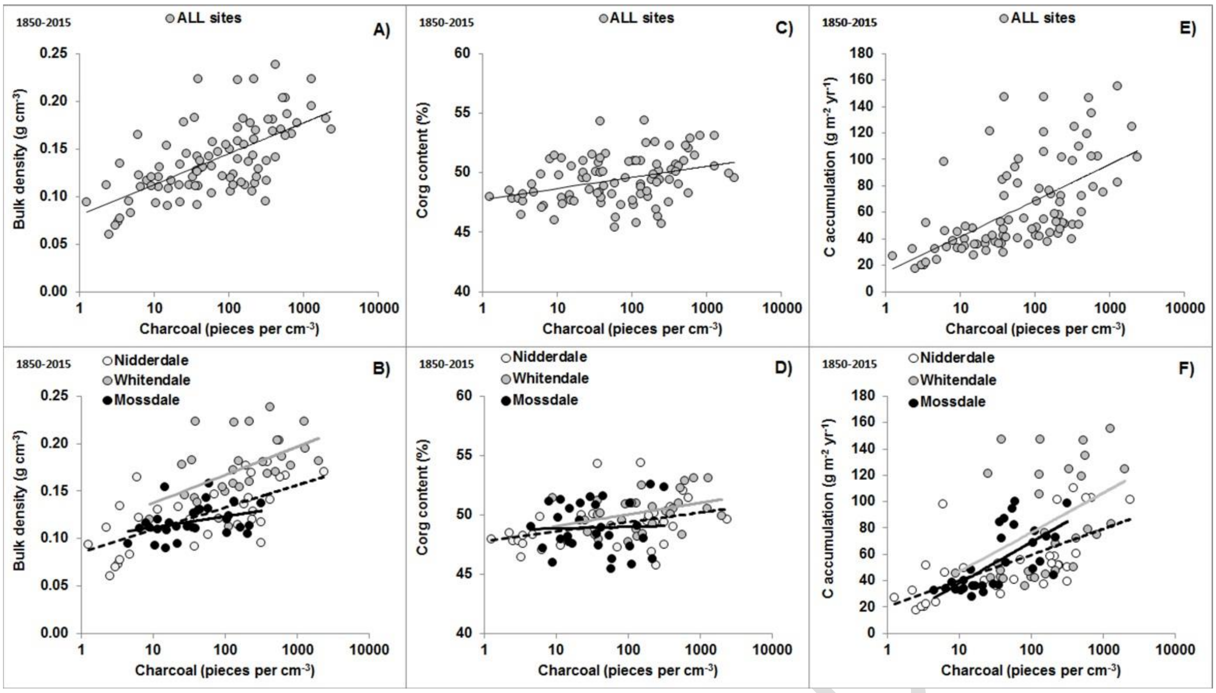


Figure 7: Bulk density (left), organic carbon (C_{org}) content (middle) and carbon accumulation (right) versus the natural logarithm of the number of charcoal pieces per cm^3 of peat (concentration) from the top 15 cm (i.e. equal to the SCP based age range of 1850-2015) of the three peat cores (in 0.5 cm sections) shown for all sites combined (A, C, E) and for individual sites Nidderdale, Mossdale and Whitendale (B, D, F). The best fit logarithmic functions are shown for combined data (thin black line) and for the individual sites (thick lines) with Nidderdale (dashed black), Whitendale (grey) and Mossdale (black). For individual equations and statistics for the regressions per site see the summary Table 2.

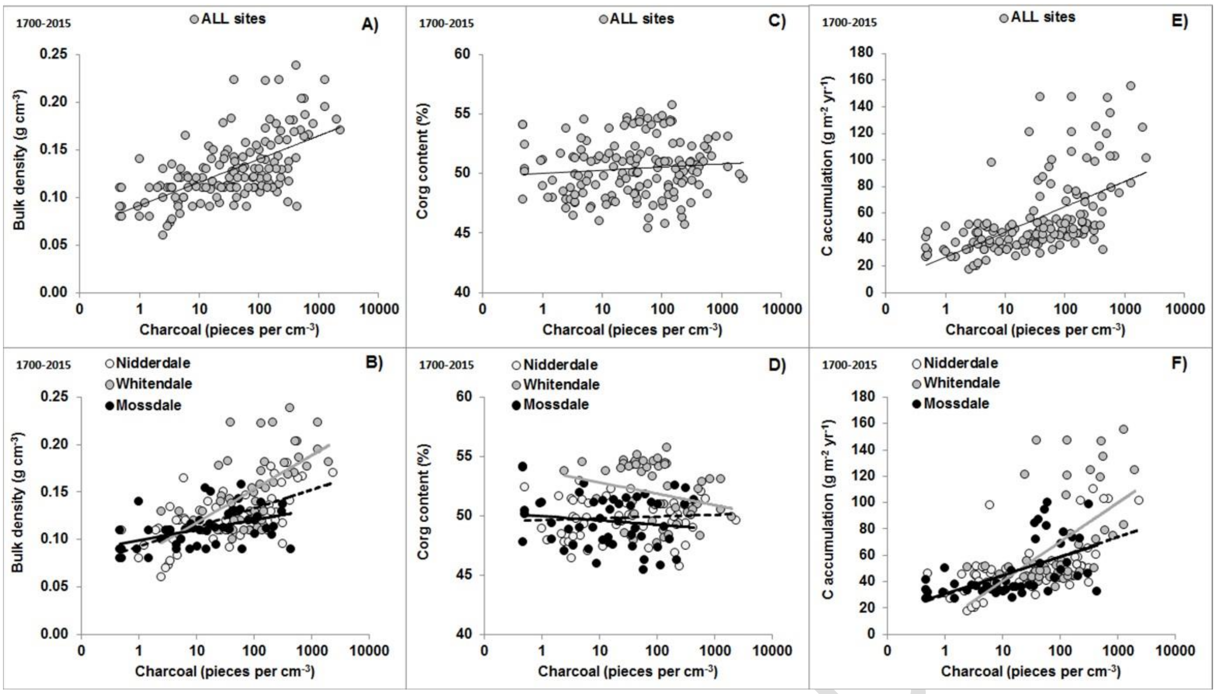
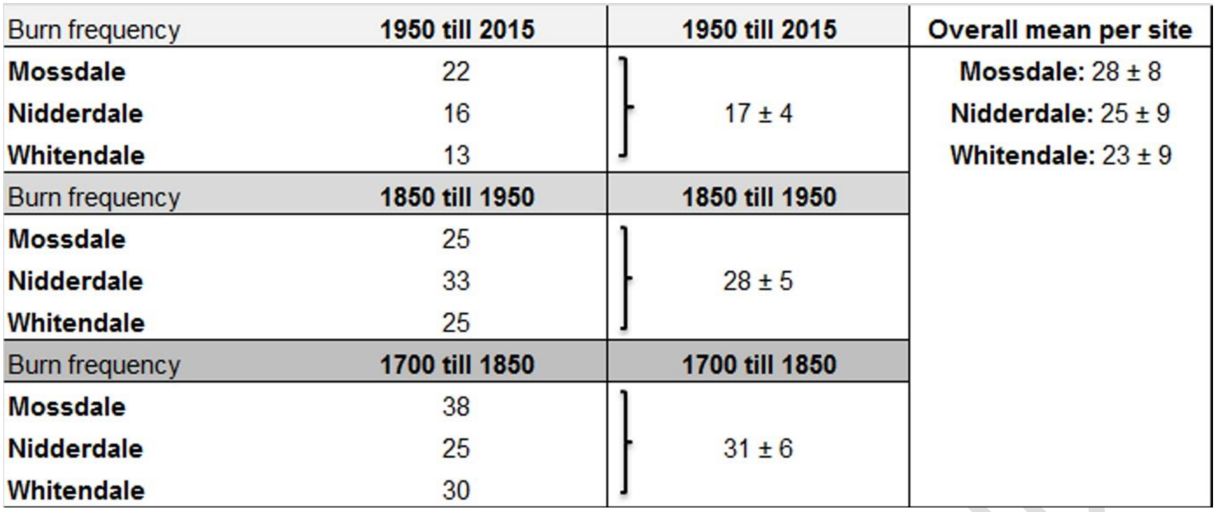
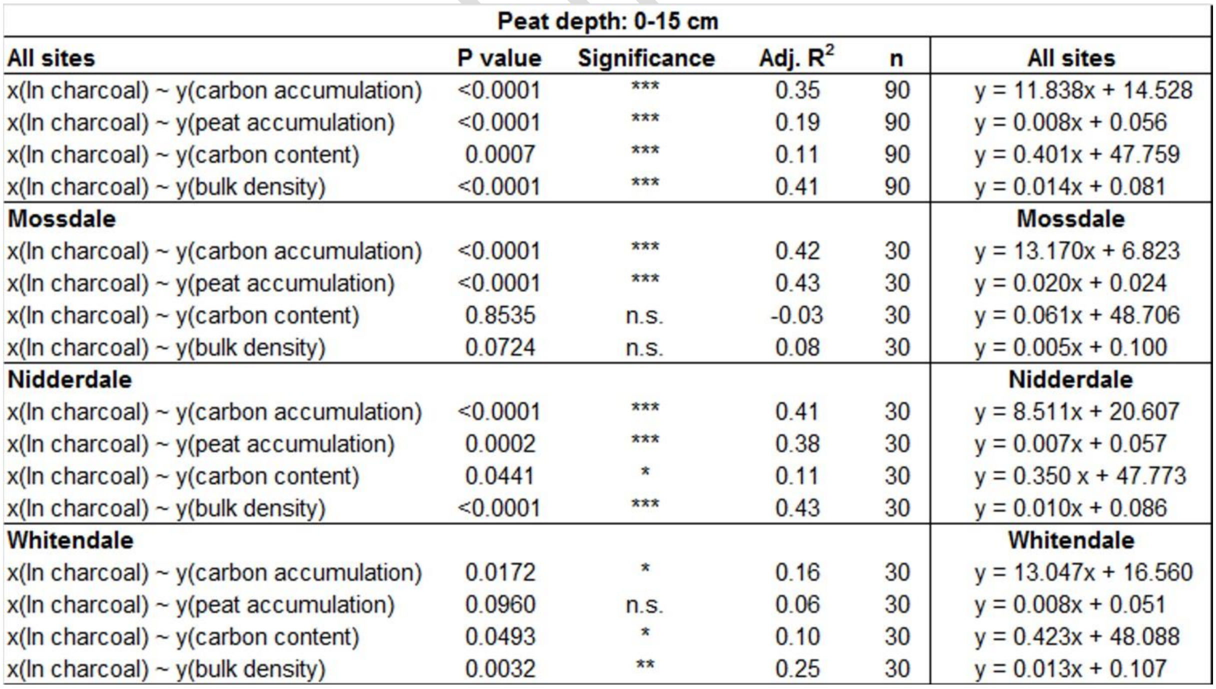


Figure 8: Bulk density (left), organic carbon (C_{org}) content (middle) and carbon accumulation (right) versus the natural logarithm of the number of charcoal pieces per cm^3 of peat (concentration) from the top 25 cm (i.e. equal to the SCP based age range of 1700-2015) of the three peat cores (in 0.5 cm sections) shown for either all sites combined (A, C, E) and for the individual sites Nidderdale, Mossdale and Whitendale (B, D, F). The best fit logarithmic functions are shown for combined data (thin black line) and for the individual sites (thick lines) with Nidderdale (dashed black), Whitendale (grey) and Mossdale (black). For individual equations and statistics for the regressions per site see the summary Table 3.



Burn frequency	1950 till 2015	1950 till 2015	Overall mean per site
Mossdale	22	17 ± 4	**Mossdale:** 28 ± 8
Nidderdale	16		**Nidderdale:** 25 ± 9
Whitendale	13		**Whitendale:** 23 ± 9
Burn frequency	**1850 till 1950**	**1850 till 1950**	
Mossdale	25	28 ± 5	
Nidderdale	33		
Whitendale	25		
Burn frequency	**1700 till 1850**	**1700 till 1850**	
Mossdale	38	31 ± 6	
Nidderdale	25		
Whitendale	30		

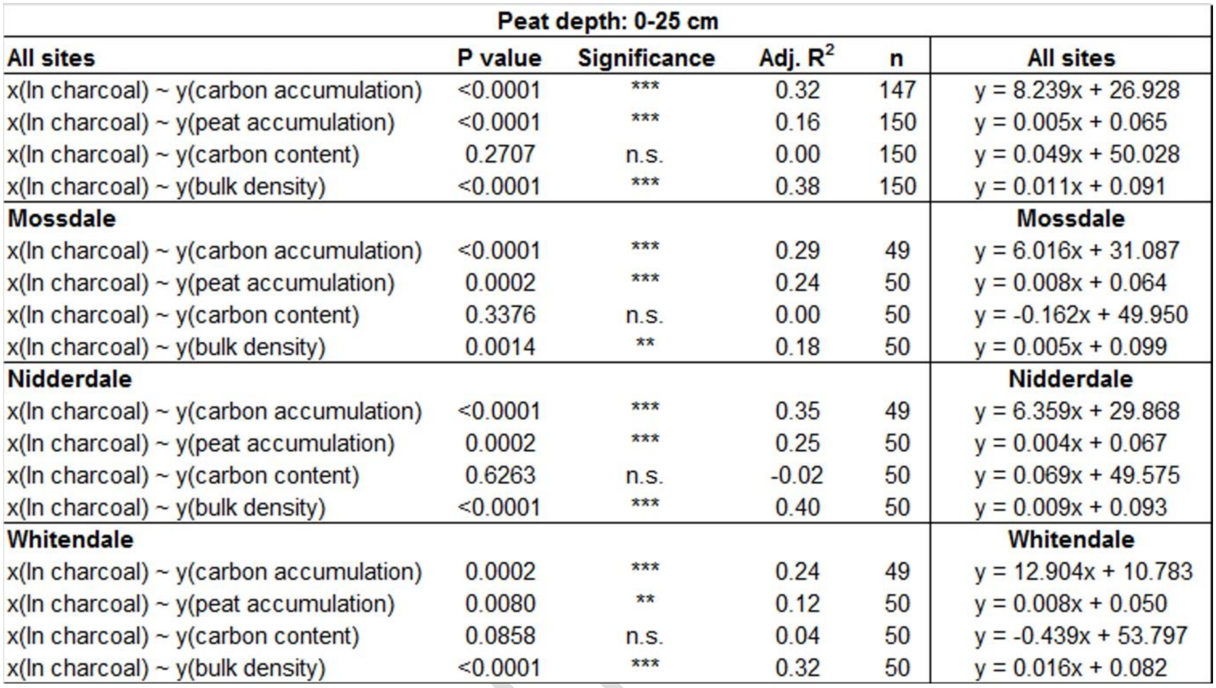
Table 1: The estimated burn frequencies per site, period and overall based on charcoal (>120 µm size) peak frequencies. Specified periods (based on spheroidal carbonaceous particle (SCP) dating) reflect average periods of different management intensity (i.e. onset of grouse management in 1850 and general intensification from 1950). Standard deviations (±) are also provided for the 1950-2015 and overall site means.



Peat depth: 0-15 cm					
All sites	**P value**	**Significance**	**Adj. R^2**	**n**	**All sites**
x(ln charcoal) ~ y(carbon accumulation)	<0.0001	***	0.35	90	y = 11.838x + 14.528
x(ln charcoal) ~ y(peat accumulation)	<0.0001	***	0.19	90	y = 0.008x + 0.056
x(ln charcoal) ~ y(carbon content)	0.0007	***	0.11	90	y = 0.401x + 47.759
x(ln charcoal) ~ y(bulk density)	<0.0001	***	0.41	90	y = 0.014x + 0.081
Mossdale					**Mossdale**
x(ln charcoal) ~ y(carbon accumulation)	<0.0001	***	0.42	30	y = 13.170x + 6.823
x(ln charcoal) ~ y(peat accumulation)	<0.0001	***	0.43	30	y = 0.020x + 0.024
x(ln charcoal) ~ y(carbon content)	0.8535	n.s.	-0.03	30	y = 0.061x + 48.706
x(ln charcoal) ~ y(bulk density)	0.0724	n.s.	0.08	30	y = 0.005x + 0.100
Nidderdale					**Nidderdale**
x(ln charcoal) ~ y(carbon accumulation)	<0.0001	***	0.41	30	y = 8.511x + 20.607
x(ln charcoal) ~ y(peat accumulation)	0.0002	***	0.38	30	y = 0.007x + 0.057
x(ln charcoal) ~ y(carbon content)	0.0441	*	0.11	30	y = 0.350 x + 47.773
x(ln charcoal) ~ y(bulk density)	<0.0001	***	0.43	30	y = 0.010x + 0.086
Whitendale					**Whitendale**
x(ln charcoal) ~ y(carbon accumulation)	0.0172	*	0.16	30	y = 13.047x + 16.560
x(ln charcoal) ~ y(peat accumulation)	0.0960	n.s.	0.06	30	y = 0.008x + 0.051
x(ln charcoal) ~ y(carbon content)	0.0493	*	0.10	30	y = 0.423x + 48.088
x(ln charcoal) ~ y(bulk density)	0.0032	**	0.25	30	y = 0.013x + 0.107

Table 2: Regression model statistics for peat and carbon accumulation rates, carbon content and bulk density against the natural log (ln) transformed charcoal concentrations over the top 15 cm peat core section (equal to the period 1850-2015) for 0.5 cm section samples (i.e. n =

30 per site; degrees of freedom were n - 2) shown in Figure 7 (either for all sites combined or the three individual sites). Significance boundaries are n.s. (non-significant), and considered significant at $p < 0.05$, ** $p < 0.01$ and *** $p < 0.001$.



Peat depth: 0-25 cm					
All sites	**P value**	**Significance**	**Adj. R^2**	**n**	**All sites**
x(ln charcoal) ~ y(carbon accumulation)	<0.0001	***	0.32	147	y = 8.239x + 26.928
x(ln charcoal) ~ y(peat accumulation)	<0.0001	***	0.16	150	y = 0.005x + 0.065
x(ln charcoal) ~ y(carbon content)	0.2707	n.s.	0.00	150	y = 0.049x + 50.028
x(ln charcoal) ~ y(bulk density)	<0.0001	***	0.38	150	y = 0.011x + 0.091
Mossdale					**Mossdale**
x(ln charcoal) ~ y(carbon accumulation)	<0.0001	***	0.29	49	y = 6.016x + 31.087
x(ln charcoal) ~ y(peat accumulation)	0.0002	***	0.24	50	y = 0.008x + 0.064
x(ln charcoal) ~ y(carbon content)	0.3376	n.s.	0.00	50	y = -0.162x + 49.950
x(ln charcoal) ~ y(bulk density)	0.0014	**	0.18	50	y = 0.005x + 0.099
Nidderdale					**Nidderdale**
x(ln charcoal) ~ y(carbon accumulation)	<0.0001	***	0.35	49	y = 6.359x + 29.868
x(ln charcoal) ~ y(peat accumulation)	0.0002	***	0.25	50	y = 0.004x + 0.067
x(ln charcoal) ~ y(carbon content)	0.6263	n.s.	-0.02	50	y = 0.069x + 49.575
x(ln charcoal) ~ y(bulk density)	<0.0001	***	0.40	50	y = 0.009x + 0.093
Whitendale					**Whitendale**
x(ln charcoal) ~ y(carbon accumulation)	0.0002	***	0.24	49	y = 12.904x + 10.783
x(ln charcoal) ~ y(peat accumulation)	0.0080	**	0.12	50	y = 0.008x + 0.050
x(ln charcoal) ~ y(carbon content)	0.0858	n.s.	0.04	50	y = -0.439x + 53.797
x(ln charcoal) ~ y(bulk density)	<0.0001	***	0.32	50	y = 0.016x + 0.082

Table 3: Regression model statistics for peat and carbon accumulation rates, carbon content and bulk density against the natural log (ln) transformed charcoal concentrations over the entire 25 cm peat core section (equal to the period 1700-2015) for 0.5 cm section samples (i.e. n = 50 per site; degrees of freedom were n - 2) shown in Figure 8 (either for all sites combined or the three individual sites). Note that for carbon accumulation only the section 0-24.5 cm could be calculated (i.e. n = 147 for all sites or n = 49 for individual sites). Significance boundaries were n.s. (non-significant), and considered significant at * $p < 0.05$, ** $p < 0.01$ and *** $p < 0.001$.

Location	Site Type	Management	Sample ID	Carbon Accumulation rates between periods		Burn Frequencies between periods (every # year)		Sampling Date	Source
				1950-1970s	1865-1950	1950-1970s	1865-1950		
Butterburn Flow	Raised Mire	NA	BFA	82.2	73.1	NA	NA	1999	Billett *et al.,* 2010 (data from Charman, 2007)
			BFB	119	39.7				
			Mean	100.6	56.4				
Lochnagar	'Alpine' Sloping Blanket Mire	Possible burning / grazing	LAB-A	56.9	39.6	NA	NA	1997	Billett *et al.,* 2010 (data from Yang *et al.,* 2001)
Mossdale	Blanket Bog	Prescribed Burn	MC3	48.1 ± 6.7	36.1 ± 5.1	30	21	2016/17	**This Study**
Nidderdale	Blanket Bog	Prescribed Burn	NC3	95.6 ± 19.2	30.5 ± 10.6	15	28	2016/17	
Whitendale	Blanket Bog	Prescribed Burn	WC3	76.3 ± 5.5	49.2 ± 11.3	15	43	2016/17	
Moor House	Blanket Bog	Prescribed Burn	MH2		30	10?	?		Garnett (1998) PhD thesis

Location	Site Type	Management	Sample ID	Carbon Accumulation rates between periods (1955 - end date)		Burn Frequencies between periods (every # year) 1955 – 2015	End date	Source
Mossdale	Blanket Bog	Prescribed Burn	MC3	74.3 ± 17.8		17	2015	**This Study**
Nidderdale	Blanket Bog	Prescribed Burn	NC3	74.2 ± 26.7		13	2015	
Whitendale	Blanket Bog	Prescribed Burn	WC3	117.4 ± 27.7		10	2015	
				Lower/ Upper Estimate				
Moor House	Blanket Bog	Prescribed Burn	VEG 1	19.6	60	10	2005	Hardie *et al.,* 2007
			VEG 2	82.6	123			
			VEG 3	>72.6	>72.6			
			SOIL 1	33.2	88			
			SOIL 2	44.6	79.8			
			SOIL 3	30.4	71			

Table 4: Comparison of C accumulation rates between the three sites in this study (± standard deviation) across several periods with burn frequencies and other sample information compared to published values for peatlands across England and Scotland. Note that the only values which are experimentally derived are from this study, Garnett (1998) and Hardie *et al*. (2007). Billett *et al*. (2010) provided a best estimate assuming 50% C content and 98% loss-on-ignition. Lochnagar is 788 m a.s.l and has ~1600 mm annual rainfall according to Yang *et al*. (2002) and Gordon *et al*. (1998) and may have been burnt (Dalton *et al*., 2005). A question mark (?) indicates a lack of information in the study. Please note the slightly different table headings for carbon accumulation rates and burn frequencies.

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